

# Passing behavior on two-lane highways

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## Abstract

Two-lane highways make up a substantial proportion of the road network in most of the world. Passing is among the most significant driving behaviors on two-lane highways. It substantially impacts the highway performance. Despite the importance of the problem, few studies attempted to model passing behavior. In this research, a model that attempts to capture both drivers' desire to pass and their gap acceptance decisions to complete a desired passing maneuver is developed and estimated using data on passing maneuvers collected with a driving simulator. 16 different scenarios were used in the experiment in order to capture the impact of factors related to the various vehicles involved, the road geometry and the driver characteristics in the model.

A passing behavior model is developed that includes choices in two levels: the desire to pass and the decision whether or not to accept an available passing gap. The probability to complete a passing maneuver is modeled as the product of the probabilities of a positive decision on both these choices. The estimation results show that modeling the drivers' desire to pass the vehicle in front has a statistically significant contribution in explaining their passing behavior. The two sub-model incorporate variables that capture the impact of the attributes of the specific passing gap that the driver evaluates and the relevant vehicles, the geometric characteristics of the road section and the driver characteristics and account for unobserved heterogeneity in the driver population.

## Keywords

Decision making; Driving simulator; Passing behavior; Two-lane highways

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## 1. Introduction

Two-lane highways make up a substantial proportion of the road network in most of the world. About 60% of all fatal crashes in member states of the Organization for Economic Co-operation and Development (OECD) occur on these roads (OECD, 1999). Passing is among the most significant driving behaviors on two-lane highways. It is a mentally complicated task (Cantin, Lavallière, Simoneau & Teasdale, 2009) that substantially impacts the highway performance. A reduction in passing opportunities leads to the formation of vehicle platoons in the traffic flow, which in turn cause a decrease in the level of service and negatively affect safety, fuel consumption and emissions. Potential improvements to the design of two-lane highways include construction of additional lanes, passing sections, 2+1 lane designs, or widening of existing lanes and shoulders. However, these solutions are costly and require careful design and evaluation prior to implementation. Thus, a better understanding of passing behavior is essential.

Despite the importance of the problem, few studies attempted to model passing behavior. Several studies developed analytical models based on equations of motion to determine required sight distances (Polus, Livneh & Frischer, 2000; Glennon, 1998; Brown & Hummer, 2000; Hassan, Easa & Abd El Halim, 1996; AASHTO, 1994). Other studies focused on prediction of numbers and frequencies of passing maneuvers depending on macroscopic traffic characteristics (Hegeman, 2004) or the impact of impatience on critical passing gaps (Pollatschek & Polus, 2005). Early studies that aimed to estimate critical passing gaps distributions (Jones & Heimstra, 1966; Farber and Silver, 1967; Gordon and Mast, 1968; Miller and Pretty, 1968) did not model the variables that affect mean critical gaps.

Passing models are also not commonly incorporated in microscopic traffic simulation models that are mainly developed to evaluate congested urban networks. To fill this gap, several specific simulation tools for two-lane highways that incorporate passing have been developed. These include TWOPAS (St. John and Harwood, 1986), TRARR (Hoban, Shepherd, Fawcett & Robinson, 1991), VTISim (Brodin & Carlsson, 1986), and RuTSim (Tapani, 2005). They use simplified passing models that are based on data collected in the 1970's. The authors of both (St. John & Harwood, 1986) and (Tapani, 2005) indicated the need for improved passing gap acceptance models.

However, few studies were conducted at the microscopic level (Clarke, Ward & Jones, 1998). An important reason for this is that passing maneuvers may occur anywhere on a section of road. As a result, field studies to collect data on passing maneuvers may be expensive and inefficient. Furthermore, they offer little control over the explanatory variables and usually no information on the drivers being observed. Driving simulators have been shown [e.g. Alicandri, 1994; Jenkins and Rilett, 2004] to be a reliable alternative to observe driving behavior. In the context of passing behavior, data collected with driving simulators have been used to by several authors. Jenkins & Rilett (2005) used simulator data to develop a classification of passing maneuvers. Bar-Gera & Shinar (2005) evaluated the impact of the speed difference between the lead and subject vehicle on drivers' desire to pass in a

simulated environment. The driving simulator scenarios were designed so that the lead vehicle first appeared at a distance of 180 m and at an initial speed that was 16 km/h lower than that of the subject. The lead vehicle then accelerated to a target speed determined by the experimental design. The design speeds were defined relative to the subject speed as -6.4, -3.2, 0, and 3.2 km/h. Negative differences mean that the lead vehicle's target speed was lower than the subject's speed. They found that in half of the cases subjects passed lead vehicles that were faster than their own average speed. However, they studied a divided highway and so did not consider vehicles in the opposing lanes and the feasibility of passing as captured for example by gap acceptance functions. Farah, Polus, Bekhor & Toledo, (2009) developed a passing gap acceptance model that takes into account the impact of the road geometry, traffic conditions and drivers' characteristics. However, this model does not consider drivers' motivation and desire to pass. In this research, a model that attempts to capture both drivers' desire to pass and their gap acceptance decisions to complete a desired passing maneuver is developed and estimated using data collected with a driving simulator.

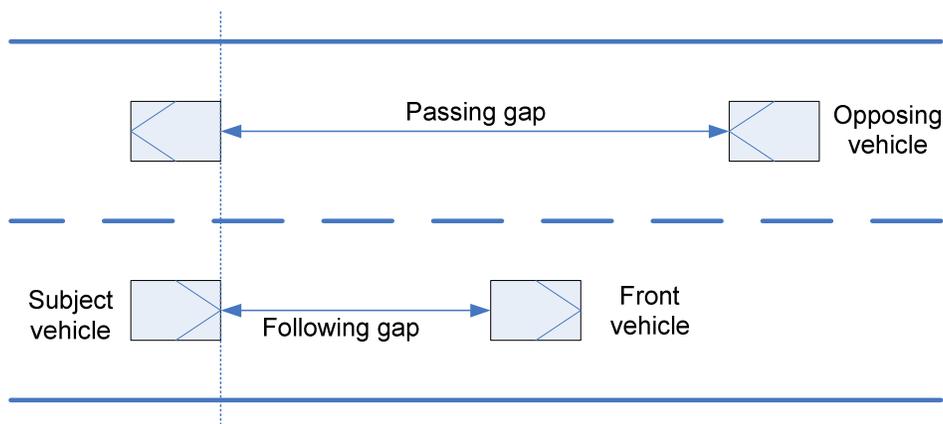
The rest of this paper is organized as follows: the next section describes the driving simulator experiment that was conducted and summarizes the data that was collected in order to estimate passing models. Then, the formulation and detailed specification of the passing behavior model are presented, followed by presentation of the estimation results for this model. Finally, the conclusions and future research are described.

## 2. Method

### 2.1. Laboratory experiment

A laboratory experiment using a driving simulator was developed in order to collect data on drivers' passing behavior. The simulator used in this experiment, STISIM (Rosenthal, 1999), is a fixed-base interactive driving simulator, which has a 60° horizontal and 40° vertical display. The changing alignment and driving scene were projected onto a screen in front of the driver. The simulator updates the images at a rate of 30 frames per second.

The situations participants encountered were defined by the vehicles shown in Fig. 1.



**Fig. 1. Definition of passing gap acceptance situation.**

The subject vehicle is following a front vehicle. This paper focuses on the subject's decision whether or not to pass this vehicle. In making this choice, the subject needs to consider the available passing gaps. These gaps are defined as the time gap between the opposing vehicle and the subject vehicle, at the time that the lead vehicle encounters the subject vehicle (as shown in Fig. 1). Mathematically, the time gap is calculated by division of the distance between the vehicles by the sum of their speeds.

In order to capture the impact of various infrastructure and traffic factors on passing behavior a number of different simulator scenarios were designed. The experiment design included four different factors. These factors were chosen based on previous studies that showed their impact on passing decisions. Two levels were used for each factor. The factors and their values are presented in Table 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 opposing lane	Drawn from truncated negative exponential distributions	
	Mean: 10.3 sec. Min: 5.0 sec., Max: 25.0 sec.	Mean: 18.0 sec. Min: 9.0 sec., Max: 31.0 sec.
Speed of lead vehicle	Drawn from uniform distributions	
	67% between 80 and 120 km/hr 33% between 40 and 80 km/hr	33% between 80 and 120 km/hr 67% between 40 and 80 km/hr
Speed of opposing vehicle	Drawn from uniform distributions	
	67% between 80 and 120 km/hr 33% between 40 and 80 km/hr	33% between 80 and 120 km/hr 67% between 40 and 80 km/hr

In addition to these factors, the type of the lead and the opposing vehicles (truck or passenger cars) were considered. The vehicle type was randomly set for each vehicle in each scenario run, and so participants in the experiment encountered both types of vehicles.

A full factorial design with these factors, which produces 16 (2<sup>4</sup>) scenarios was used. Following (Farah et al., 2009), it was decided that participants complete four scenarios, which take about 40 minutes. The partial confounding method [see e.g. (Hicks & Turner, 1999)] was used to allocate the block of scenarios each participant will complete. This method is designed to maintain identification of the main and

lower level interaction effects of the various factors. In the design of this experiment third level interactions were confounded.

All scenarios in the experiment included 7.5 km two-lane highway sections with no intersections. In all scenarios, the sections were on level terrain and with daytime and good weather conditions, which allowed good visibility. Fig. 2 shows a snapshot of the driver's view in the simulator.



**Fig. 2. Snapshot from the driving simulator scenario.**

Drivers were instructed to drive as they would normally do in the real world. Following previous studies (Bar-Gera & Shinar, 2005; Farah, Yechiam, Bekhor, Toledo & Polus, 2008) drivers were given between 5 and 10 minutes to become familiar with the simulator.

## **2.2. Participants**

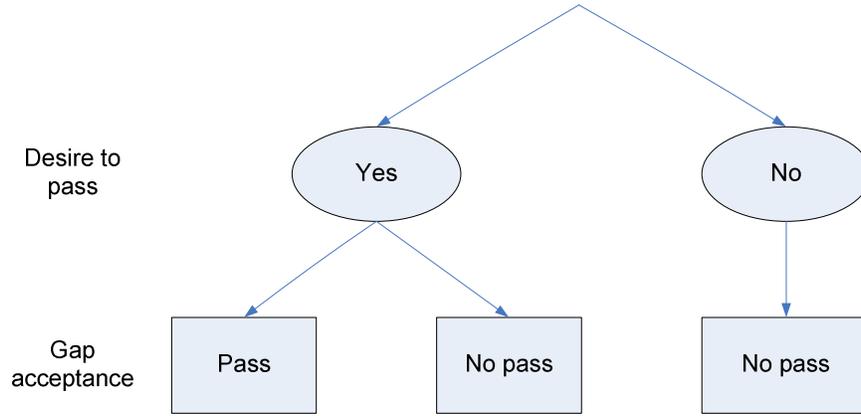
100 drivers (69 males, 31 females) who had a driving license for at least 5 years and drove on a regular basis participated in the experiment. The age of the participants ranged between 21 and 61 years, with a mean of 32.7 years and standard deviation 9.8 years.

## **2.3. Data collection**

The simulator collected data on the longitudinal and lateral position, speed and acceleration of the subject vehicle and all other vehicles in the scenario at a resolution of 0.1 seconds. From this raw data, other variables of interest, such as the times and location of passing maneuvers, distances between vehicles and relative speeds were calculated. The resulting data set included a total of 14654 passing gap observations. In 696 (4.7%) of these gaps, the drivers completed passing maneuvers.

### 3. Model formulation

The completion of passing maneuvers is modeled in two stages: the desire to pass and the decision whether to accept or reject an available passing gap. This model structure is shown in Fig. 3.



**Fig. 3. Structure of the passing model.**

Drivers are first assumed to decide whether or not they want to pass the lead vehicle. Drivers that are interested in passing then evaluate the available passing gap and either accept it and complete the passing maneuver, or reject it and do not complete the maneuver.

#### 3.1 Desire to pass model

The desire to pass is formulated as a binary choice problem:

$$DP_{nt} = \begin{cases} 1 & \text{if } U_{nt}^{DP} \geq 0 \\ 0 & \text{if } U_{nt}^{DP} < 0 \end{cases} \quad (1)$$

Where,  $n$  and  $t$  are indices for the driver and the passing gap, respectively.  $DP_{nt}$  is the choice indicator variable with value 1 if the driver desires to pass and zero otherwise.  $U_{nt}^{DP}$  is the utility to the driver from desiring to pass. The utility of the other alternative, not desiring to pass is assumed to equal zero. The desire to pass utility is unobserved and modeled as a random variable, with a mean which is a function of explanatory variables:

$$U_{nt}^{DP} = X_{nt}^{DP} \beta^{DP} + \alpha^{DP} v_n + \varepsilon_{nt}^{DP} \quad (2)$$

Where,  $X_{nt}^{DP}$  and  $\beta^{DP}$  are a vectors of explanatory variables and the corresponding parameters, respectively.  $v_n$  is an individual-specific error term that captures the effect of unobserved drivers' characteristics, such as aggressiveness and level of skill, on their desire to pass. It is constant for a given driver, and so introduces correlations between the observations obtained from a given driver. The model assumes that conditional on the value of this latent variable, the observations of a given driver are independent.  $\alpha^{DP}$  is the parameter of  $v_n$ .  $\varepsilon_{nt}^{DP}$  is a random error term.

Assuming that  $\varepsilon_{nt}^{DP} \sim N(0, \sigma^{DP})$ , the desire to pass probability conditional on the value of  $v_n$  is given by:

$$P(DP_{nt} = 1 | v_n) = \Phi\left(\frac{X_{nt}^{DP} \beta^{DP} + \alpha^{DP} v_n}{\sigma^{DP}}\right) \quad (3)$$

Where,  $\Phi(\cdot)$  is the cumulative normal distribution function. For identification of the model in estimation,  $\sigma^{DP}$  is normalized to 1.

### 3.2 Gap acceptance model

Drivers that desire to pass, evaluate the available passing gaps against their critical gap, which is the minimum acceptable gap. The driver passes the front vehicle if the available gap is acceptable (i.e. larger or equal to the critical gap) and does not pass if the gap is rejected:

$$A_{nt} = \begin{cases} 1 & \text{if } G_{nt} \geq G_{nt}^{cr} \\ 0 & \text{if } G_{nt} < G_{nt}^{cr} \end{cases} \quad (4)$$

Where,  $A_{nt}$  is a choice indicator variable with value 1 if the gap is accepted and zero otherwise.  $G_{nt}$  and  $G_{nt}^{cr}$  are the available passing gap and the critical passing gap, respectively.

Critical gaps are unobserved and therefore modeled as random variables. Their means are a function of explanatory variables. Critical gaps are modeled as random variables in order to capture the probabilistic nature of gap acceptance decisions. A logarithmic transformation is used in order to guarantee that critical gaps are always positive:

$$\ln(G_{nt}^{cr}) = X_{nt}^G \beta^G + \alpha^G v_n + \varepsilon_{nt}^G \quad (5)$$

Where,  $X_{nt}^G$  and  $\beta^G$  are vectors of explanatory variable and the corresponding parameters.  $\alpha^G$  is the parameter of  $v_n$ .  $\varepsilon_{nt}^G$  is a random error term.

Assuming that  $\varepsilon_{nt}^G \sim N(0, \sigma^G)$ , the probability that a passing gap is acceptable, conditional on  $v_n$  is given by:

$$P_n(A_{nt} = 1 | v_n) = \Phi \left[ \frac{\ln(G_{nt}) - X_{nt}^G \beta^G + \alpha^G v_n}{\sigma^G} \right] \quad (6)$$

### 3.3 Likelihood function

The conditional probability to complete a passing maneuver is given by the product of the probability to desire to pass and the probability to accept a passing gap:

$$P_{nt}(Y_{nt} = 1 | v_n) = P_{nt}(DP_{nt} = 1 | v_n) P_{nt}(A_{nt} = 1 | DP_{nt} = 1, v_n) \quad (7)$$

Where,  $Y_{nt}$  is an indicator that takes a value of 1 if driver  $n$  passed the vehicle in front using gap  $t$ , and 0 otherwise.

The conditional probability of single observation is given by:

$$P_{nt}(Y_{nt} | v_n) = P_{nt}(Y_{nt} = 1 | v_n)^{Y_{nt}} P_{nt}(Y_{nt} = 0 | v_n)^{1 - Y_{nt}} \quad (8)$$

The joint probability of the sequence of  $T$  observations for the same driver is given by:

$$P_{nt}(Y_{n1}, Y_{n2}, \dots, Y_{nT} | v_n) = \prod_{t=1}^T P_{nt}(Y_{nt} | v_n) \quad (9)$$

It is assumed that the distribution of  $v_n$  in the driver population is standard normal. The unconditional joint probability of the observation for a given driver is obtained by integrating over this distribution:

$$P_{nt}(Y_{n1}, Y_{n2}, \dots, Y_{nT}) = \int_{-\infty}^{+\infty} P_{nt}(Y_{n1}, Y_{n2}, \dots, Y_{nT} | v) \phi(v) dv \quad (10)$$

Finally, the log-likelihood function is given by:

$$LL = \sum_{n=1}^N \ln[P_{nt}(Y_{n1}, Y_{n2}, \dots, Y_{nT})] \quad (11)$$

## 4. Results

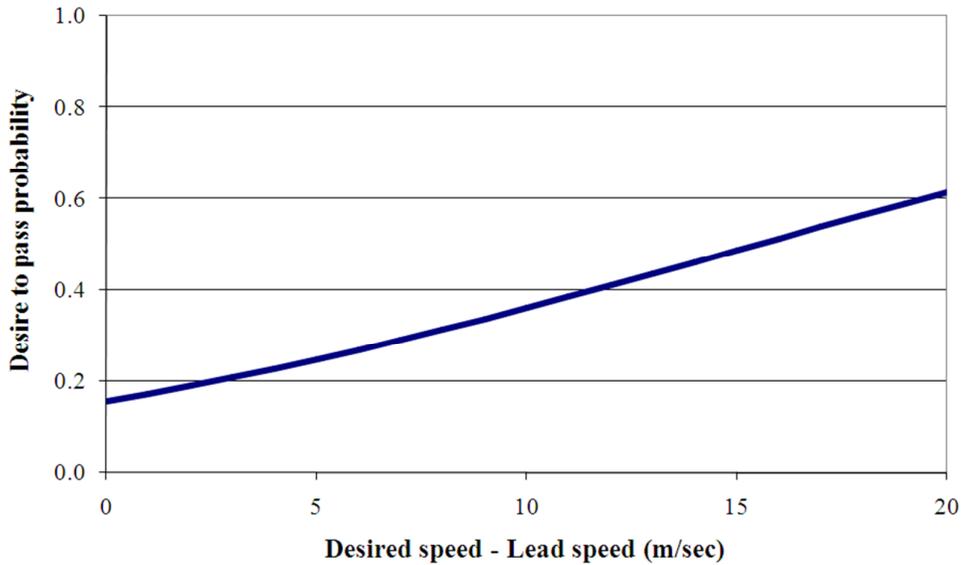
Table 2 presents the estimation results of the passing model defined above.

**Table 2**

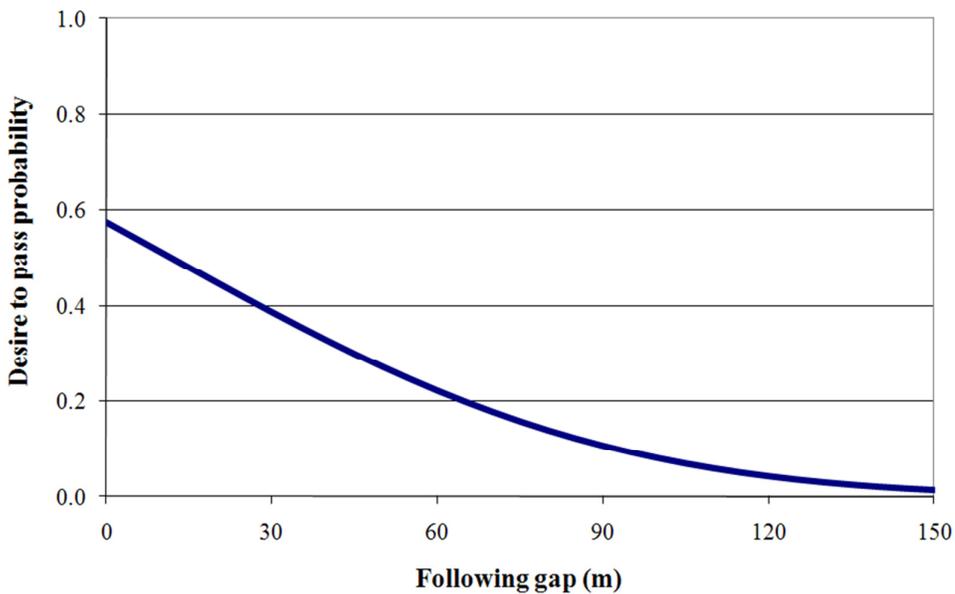
**Estimation results for the passing model**

Variable	Coeff. (t-stat)
<b>Desire to pass</b>	
Constant	-0.5337 (-4.47)
(Desired speed – Lead speed) (m/sec)	0.0652 (7.89)
Following distance (m.)	-0.0159 (-17.6)
Cumulative distance (km)	0.0147 (2.42)
$\alpha^{DP}$	0.4723 (6.53)
<b>Gap acceptance</b>	
Constant	2.9902 (30.2)
Subject speed (m/sec)	-0.0407 (-10.0)
Front vehicle speed (m/sec)	0.0306 (5.57)
Oposing vehicle speed (m/sec)	-0.0086 (-3.09)
Road curvature (1/km.)	0.1036 (10.9)
Type of front vehicle (1 = truck, 0 = car)	0.0724 (1.819)
Age under 25	-0.1556 (-2.29)
$\alpha^G$	-0.2056 (-5.87)
$\sigma^G$	0.2780 (7.20)
Null LL = -2056.75, Maximum LL = -1298.45	
Adjusted Rho-squared: 0.37	

All the variables in the model are statistically significant at the 95% confidence level. The desire to pass is affected by the difference between the desired speed of the subject driver and the current speed of the vehicle in front and by the following distance. Fig. 4 and Fig. 5 illustrate the impact of the difference between the desired speed and the front vehicle speed and of the following clear gap on the probability to desire passing, respectively. Unless varied, the figures are based on the assumption that the desired speed is 40 km/hr (11.1 m/sec) higher than the front speed and that the following clear gap is 30 meters.



**Fig. 4. Impact of the difference between the desired speed and the front vehicle speed on the desire to pass probability.**



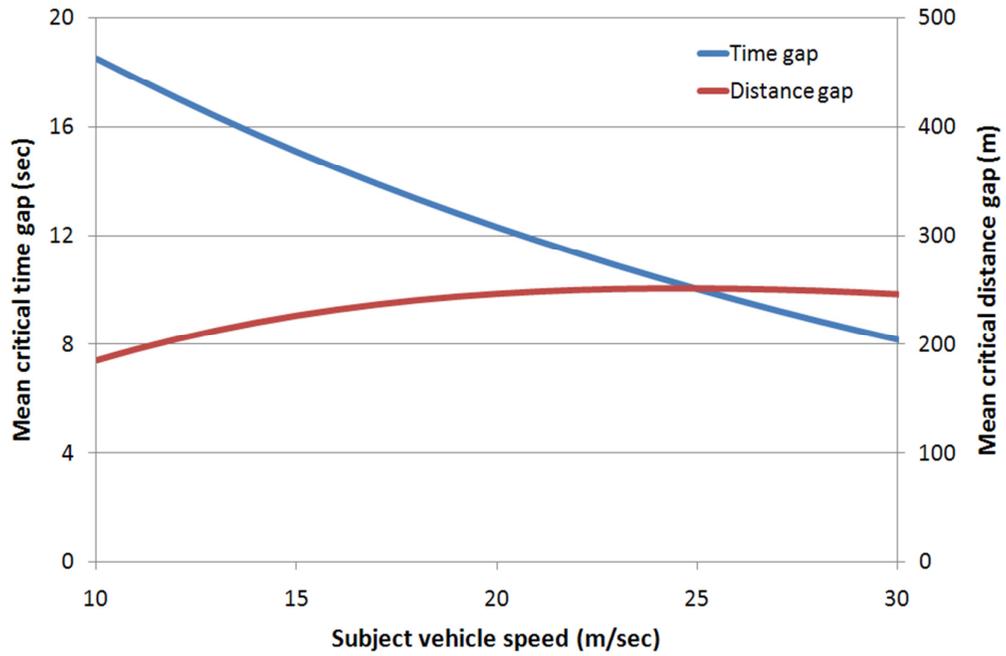
**Fig. 5. Impact of the following clear gap on the desire to pass probability.**

The difference between the desired speed and the lead speed variable captures the extent that the front vehicle imposes a constraint on the speed of the subject. In the data, the desired speed for each driver was calculated as the mean speed of the vehicle in the sections that it was not close to the vehicle in front. As expected, the value of the coefficient of this variable is positive, which indicates that drivers are more likely to attempt to pass when the vehicle in front is slower relative to their desired speed. Similarly, the desire to pass is higher when the distance between the subject and the front vehicle is lower. Note from Fig. 4 that the probability to desire to pass is not negligible even when the lead vehicle speed is equal to the desired speed. This result

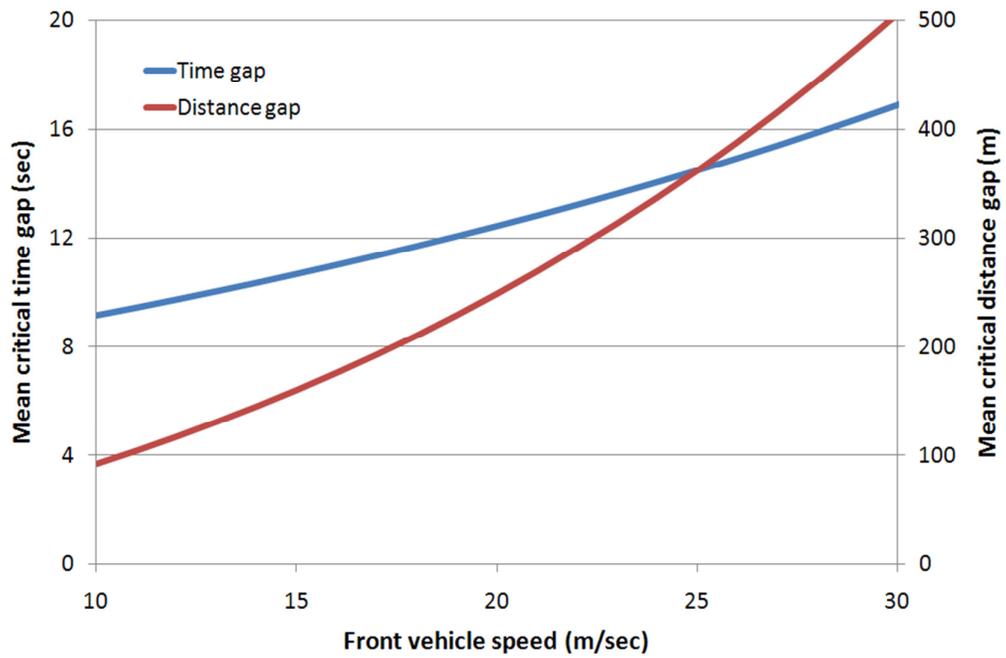
is consistent with those of Bar-Gera & Shinar (2005) who found that in half of the cases drivers passed lead vehicles that were faster than their own average speed.

The collection of driving simulator data may lead to biases in the behavior. For example, simulator drivers may be indifferent or become tired with the experiment as it progresses and so modify their behavior. The cumulative distance variable, which is defined as the total distance the subject has driven from the beginning of the experiment to the measurement point, aims to correct this effect. It has a small, but significant, positive effect on the desire to pass probability. Thus, the desire to pass increases as the experiment progresses, possibly in order that the subject completes the task sooner. Note that this variable intends to correct biases in the experiment and therefore should be omitted from the model when it is applied for prediction.

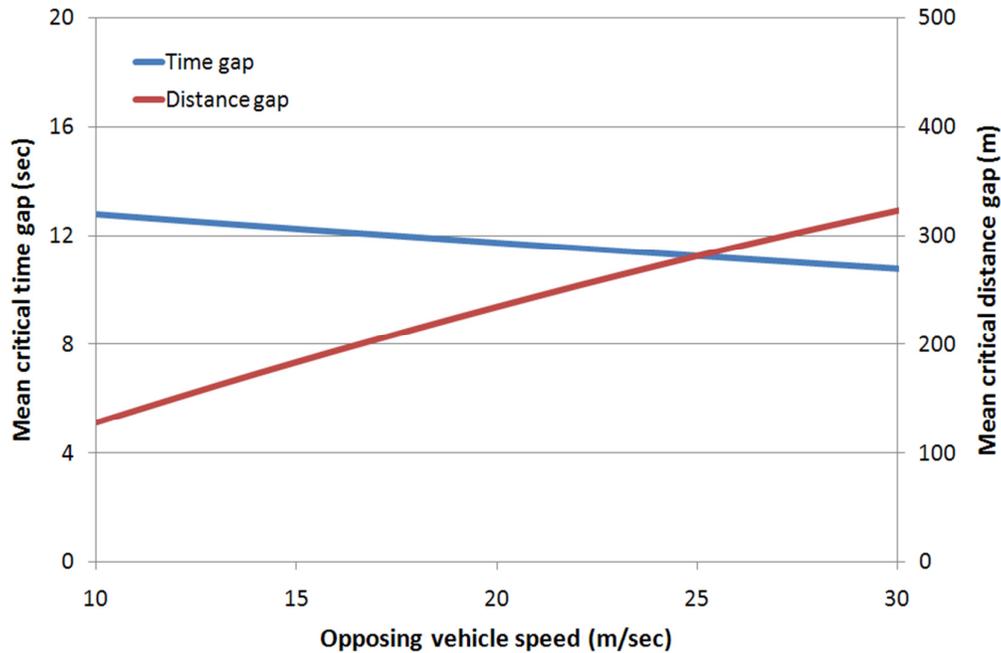
The passing gap acceptance decisions are affected the most by the variables related to the speeds of the subject vehicle and the other relevant vehicles: the vehicle in front and the opposing vehicle. Mean critical passing gaps are larger when the speed of the subject vehicle is higher and when the speed of the vehicle in front is lower. This is intuitive because it is more difficult to complete the passing maneuver as it requires more time and longer distances. The type of front vehicle also affects the critical gaps. It is larger for trucks, which obscure the field of vision and pose a higher safety risk, compared to passenger cars. In contrast, critical gaps decrease when the speed of the opposing vehicle increases. Note that critical gaps are measured in time units. Therefore, higher speed of the opposing vehicle results in larger critical gaps in terms of distance. Therefore, the results indicate that critical gaps decrease with the speed of the opposing vehicle in terms of time, but increase in terms of distance. Fig. 6, Fig. 7 and Fig. 8 illustrate the impact of the speeds of the subject, the vehicle in front and the opposing vehicle on the mean critical gap both in terms of time and distance, respectively. In each of the figures, one variable was varied while all the other variables were fixed. The critical gaps were calculated for a female driver over 25 years old driving on a tangent section (0 curvature). Unless varied the figures assume that the subjects speed is 80 km/hr (22.2 m/sec), the speed of the vehicle in front, which is a passenger car, is 60 km/hr (16.7 m/sec) and the speed of the opposing vehicle is 90 km/hr (25.0 m/sec).



**Fig. 6. Impact of the subject speed on the mean critical gap.**



**Fig. 7. Impact of the front vehicle speed on the mean critical gap.**

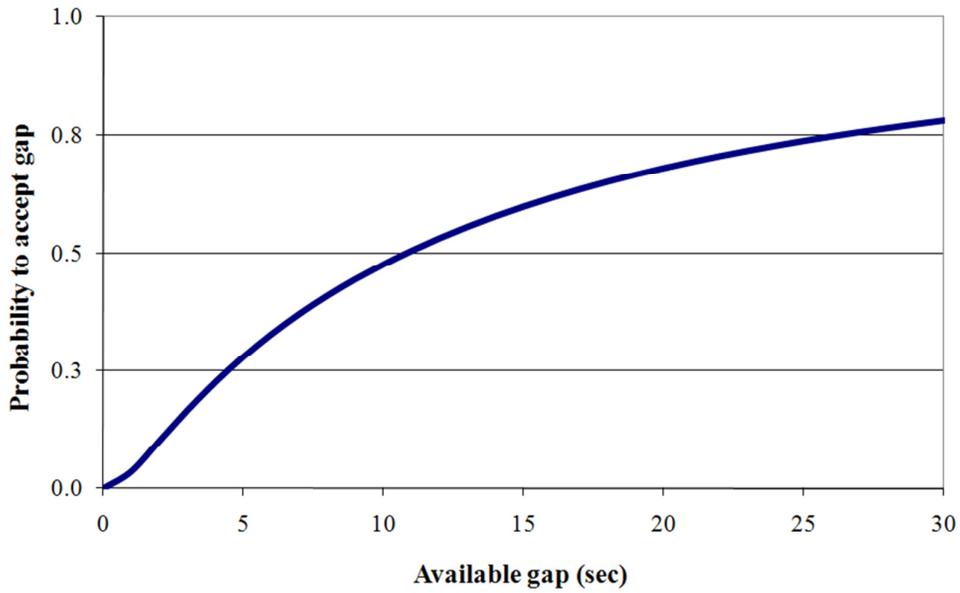


**Fig. 8. Impact of the opposing vehicle speed on the mean critical gap.**

It should be noted that two variables that capture drivers' impatience were also examined: the number of rejected gaps and the waiting time from the moment the subject was interrupted by the lead vehicle. The effect of neither of these variables was statistically significant and therefore they were not included in the final model.

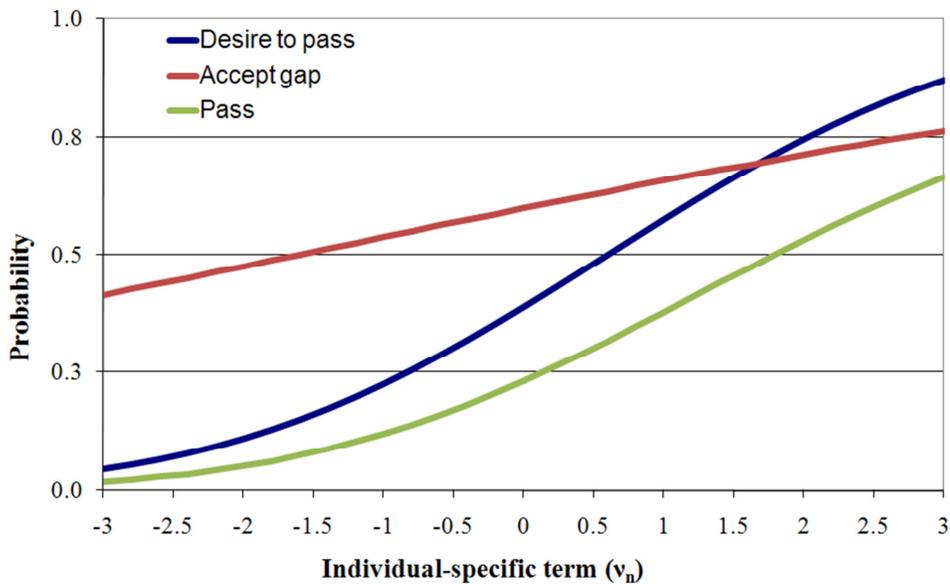
The geometric design of the road also affects passing behavior. In this model, this is captured by the road curvature. Critical gaps are smaller in roads with large curve radii, which allow larger sight distances, compared to road with tighter curves.

Critical passing gaps vary substantially with drivers' characteristics. They are significantly smaller for younger drivers compared to older ones. This result is consistent with previous studies that found that young drivers tend to behave more aggressively and take more risks [e.g. (Evans, 2004)]. The gender of drivers was not found to be statistically significant. Finally, the size of the available gap clearly affects passing gap acceptance, with higher acceptance probabilities for larger gaps. This result is illustrated in Fig. 9. The assumed values of the explanatory variables are as described above.



**Fig. 9. Impact of the available gap on gap acceptance probabilities.**

The individual-specific error term  $v_n$ , which captured latent driver characteristics, was statistically significant in both parts of the model. The parameters of this term were positive in the desire to pass model and negative in the gap acceptance model. This result is consistent with an interpretation of this term as representing aggressiveness and level of skill. Aggressive drivers (with high  $v_n$  values) are more likely to desire to pass, and when they do have lower critical gaps compared to timid drivers. The effect of this term is illustrated in Fig. 10.



**Fig. 10. Impact of the individual-specific term on passing probabilities.**

The figure shows the variation of the probabilities to desire to pass, to accept the available gap and the overall probability of completing the passing maneuver with the value of  $v_n$ . For this figure, it is further assumed that the available gap is 15 seconds.

In order to examine the usefulness of the model structure presented above, it was compared against a simpler model that only included a single-step gap acceptance decision. The likelihood value at convergence of this model was 1670.78 with 9 parameters. The simpler model can be viewed as a restricted case of the model presented here, with the probability of the desire to pass set at 1. Therefore, a likelihood ratio test can be conducted. The test statistic is 744.66. It is distributed  $\chi^2$  with 5 degrees of freedom, which supports adopting the two-stage model and rejecting the simpler model.

## 5. Summary and conclusions

This paper studied passing behavior on two-lane highway. The passing decision choice is modeled in two levels: the desire to pass and the decision whether or not to accept an available passing gap. The probability to complete a passing maneuver is modeled as the product of the probabilities of a positive decision on both these choices. Data on passing maneuvers was collected with an interactive driving simulator in a laboratory environment. 16 different scenarios were used in order to capture the impact of factors related to the various vehicles involved, the road geometry and the driver characteristics in the model.

The estimation results show that modeling the drivers' desire to pass the vehicle in front has a statistically significant contribution in explaining their passing behavior. The two sub-model incorporate variables that capture the impact of the attributes of the specific passing gap that the driver evaluates and the relevant vehicles, the geometric characteristics of the road section and the driver characteristics. Variables related to the gap itself include the size of the available passing gap, the speeds of the subject vehicle, the vehicle in front and the opposing vehicle, the following gap between the front vehicle and the subject and the type of the front vehicle. The road geometry is captured by the horizontal curvature. The driver characteristic that was found to be significant is the driver's age. In addition, a latent characteristic error term that was used in the model, revealed significant heterogeneity in passing behavior in the driver population.

While the results reported here are promising, this work has limitations that merit further research in several directions. Possibly the most important limitation is that the model estimation used only data from a driving simulator. The estimation results need to be validated against real-world data to eliminate biases resulting from the use of simulator. Unfortunately, detailed data on passing behavior is difficult to collect because of the spatial extent of the locations where these maneuvers may take place. Aggregated data on vehicle passage times at various points in a section of road, which is more readily available, may also be used for this purpose. The effect of the geometric design on passing behavior was captured only through the road curvature. This is partly because important design parameters, such as those related to the quality of the pavement, sight distances or the road side features, are difficult to model and to

perceive in the simulator. Again, real-world data is needed to enhance the models in this direction. In addition to improving our understanding of drivers' behavior, the intended practical application of the model presented in this paper is in the framework of traffic simulation models. This would require additional extensions to handle situations, such as aborted passing maneuvers and overtaking multiple vehicles in a single pass. Finally, car crashes are an important problem with two-lane highways. Passing is an important factor in car crashes on two lane highway. However, Clarke, Ward & Jones (1998) showed that errors in the evaluation of passing gaps are not the only cause for passing crashes. In addition, many crashes were collisions with the lead vehicle, with an opposing vehicle that was initially obscured from view or single-vehicle crashes resulting from the dynamics of the passing maneuver. Therefore, safety indicators related to passing maneuvers need to be developed and the impact of different geometric, traffic and driver characteristics on the risk and severity of car crashes in these roads need to be further studied.

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