A PASSING GAP ACCEPTANCE MODEL FOR TWO-LANE RURAL HIGHWAYS

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Passing maneuvers on rural two-lane highways significantly affect highway capacity, safety, and level of service. This paper presents an analysis of data on drivers' passing decisions on two-lane rural highways that were collected with an interactive driving simulator. Measurements of the speeds and positions of all vehicles in several different scenarios were collected and processed to generate observations of gap acceptance behavior. In addition, participants responded to a questionnaire which collected information on their socio-demographic and driving styles characteristics.

These data were utilized to develop a model that explains the decision whether to pass or not, using variables that capture the impact of the road geometry, traffic conditions and drivers' characteristics. It was found that while the traffic related variables had the most important affect on passing decision, factors related to the geometric design and the driver characteristics also had a significant affect on these decisions.

KEYWORDS: Passing, gap acceptance, driving style, driving simulator, two-lane rural highways

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1. INTRODUCTION

Passing maneuvers on rural two-lane highways significantly affects capacity, safety, and level of service (Polus et al. 2000). This maneuver, which involves driving in the lane of the opposing traffic direction, is associated with an increase in the risk of a crash (Bar-Gera and Shinar 2005). Studies using self-report ratings indicate that most drivers are indeed aware that passing is a risky maneuver (Harris 1988). Thus, understanding of drivers` passing behavior and their decision making on two-lane rural highways can significantly contribute to safety analysis, level of service evaluations and the fidelity of traffic simulation models. However, only limited research has been conducted to develop models that capture passing decision-making, partly as a result of the difficulty to collect detailed data on passing behavior in the real-world.

Passing maneuvers may occur anywhere on a section of road. This causes field studies to collect data on passing gap acceptance be very expensive and inefficient. Furthermore, field studies offer little control over the intervening variables, and usually no information on the drivers being observed. In this paper, passing decisions are modeled using data that were collected in a laboratory experiment, in which participants completed a driving simulator session and a self-report questionnaire. Various studies (e.g. Alicandri 1994, Jenkins and Rilett 2004) have shown that observations derived from driving simulators are a reliable source of data to study drivers' behavior.

The rest of the paper is organized as follows: first, a review of the literature on gap acceptance modeling and in particular in the context of passing is presented. Next, the driving simulator experiment design and data collected are described, followed by the specification of passing gap acceptance models, their estimation results and analysis of the main findings. Finally, some concluding remarks and discussion are presented.

2. LITERATURE REVIEW

Gap acceptance models are widely used to capture drivers' decision to undertake various maneuvers, such as crossing an intersection, entering a roundabout or changing lanes (e.g. Mahmassani and Sheffi 1981, Polus et al. 2003, Toledo 2007). These models assume the existence of a latent critical gap, which is the value at which drivers are indifferent between accepting and rejecting a gap in traffic. Critical gaps may depend on various variables related to traffic flow characteristics, geometric design and driver characteristics. For example, in the context of stop controlled intersections, Mahmassani and Sheffi (1981) modeled the mean critical gap as a function of the number of rejected gaps (or waiting time at the stop line), which captures drivers' impatience and frustration. Similar impatience factors as well as other explanatory variables have been proposed by Madanat et al. (1993), Polus et al. (2003) and Shiftan et al. (2003) among others. Hamed et al. (1997) found that driver socioeconomic characteristics and the trip purpose also affect critical gaps.

Despite the importance of the problem, relatively few studies were conducted on modeling gap acceptance behavior in the context of passing behavior. Early studies in this area discussed drivers' perception of the required gaps for passing. For example, Jones and Heimstra (1966) studied the ability of drivers to estimate the last safe moment for passing a vehicle with another vehicle approaching. They found that in nearly 50% of the cases drivers underestimated the time risk associated with the maneuver. Other studies focused on examining the main components of the passing process and factors which affect this process, such as the required sight distances (Glennon 1998, Polus et al. 2000, AASHTO 2004). For example, Polus et al. (2000) studied successful passing maneuvers to determine the required sight distances for various combinations of design speeds and traffic conditions based on estimates of passing distances. They found that passing distances depend on the speed of the vehicle being passed.

Bar-Gera and Shinar (2005) conducted a driving simulator experiment to assess the differences in speed between the subject and a lead vehicle that prompt drivers to pass. The simulator scenario did not include any traffic in the opposite direction and so gap acceptance was not assessed. Clarke et al. (1999) analyzed 973 accident files and reported on the various ways in which inappropriate passing can lead to road accidents. Pollatschek and Polus (2005) quantified driver's impatience during passing maneuvers. They found that critical gaps decrease with an increase in two-way hourly volume.

Harwood et al. (1999) note that most of the studies on passing maneuvers are based on aggregate data or simulator data, since detailed real-world data on passing decisions are difficult to collect. They suggest that simulation models of passing maneuvers need to be developed and enhanced. To that end, models that explain drivers' passing gap acceptance decisions are important. Tools that incorporate these capabilities can help the evaluation of various road design schemes, such as the construction of passing lanes in parts of the highway. To overcome the difficulty of data collection, a driving simulator was used in this study in order to collect data on passing behavior.

3. EXPERIMENT DESIGN

A laboratory experiment using a driving simulator was developed in order to collect data on drivers' passing behavior. The laboratory experiment consisted of two parts: a questionnaire and a driving simulator session. Participants responded to a questionnaire which collects socioeconomic information, such as age, gender, marital status, education, income and records of past involvement in car crashes. In addition to the personal information, the questionnaire included the multidimensional driving style inventory scale (MDSI, Taubman Ben-Ari et al. 2004). The MDSI is a 6-point scale, which consists of 44 items that are used to calculate factor scores for each respondent in four driving styles categories:

1. Reckless and careless driving, which refers to deliberate violations of safe driving norms, and the seeking of sensations and thrill while driving. It characterizes persons who drive at high speeds, pass other cars in no-passing zones, and drive while intoxicated.
2. Anxious driving, which reflects feelings of alertness and tension as well as ineffective engagement in relaxing activities during driving.
3. Angry and hostile driving, which refers to expressions of irritation, rage, and hostile attitudes and acts while driving, and reflects a tendency to act aggressively on the road, curse, blow horn, or "flash" to other drivers.
4. Patient and careful driving, which refers to planning ahead, attention, patience, politeness and calmness while driving as well as obedience to traffic rules.

The simulator used in this experiment is STISIM (Rosenthal 1999). STISIM 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. Each participant drove 4 different scenarios with a break of 1-2 minutes between scenarios. Four different factors were considered in the construction of the simulator scenarios. Two levels were used for each factor. The factors and their different values are presented in Table 1.

TABLE 1: Factors included in the experimental design

Factor	High	Low
Geometric design	Design speed: 100 km/hr Lane width: 3.75 m. Shoulder width: 2.25 m. Curve radius: 1500-2500 m.	Design speed: 80 km/hr Lane width: 3.30 m. Shoulder width: 1.50 m. Curve radius: 300-400 m.
Opposing lane traffic volume	400 veh/hr	200 veh/hr
Speed of lead vehicle	80 km/hr	60 km/hr
Vehicle speed on opposing lane	85 km/hr	65 km/hr

All scenarios in the experiment included 7.5 km two-lane rural 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. The speeds of all vehicles in the scenario, except the subject itself, were constant in order to allow control of the sizes and distribution of passing gaps. Figure 1 shows snapshots of the drivers' view. Drivers were instructed to drive as they would normally do in the real world and were given between 5 and 10 minutes to become familiar with the simulator.

FIGURE 1: Snapshots of a road section

A full factorial 2^4 design with the factors presented in Table 1 produces 16 possible scenarios. However, pilot runs suggested that participants could only complete 4 scenarios, which take about 45 minutes in order to allow the experiment to be completed within 1 hour (on average the questionnaire took about 15 minutes to complete). Therefore, the partial confounding method was used to determine the scenarios each participant will complete. This method is designed for experiments in which the number of scenarios that can be run in a block is less than the total number of factor combinations, and so some effects have to be confounded. In the current experiment third level interactions were confounded. The order of scenarios presented to the participants may also affect the results. Therefore, different orders of the scenarios were used when blocks were replicated.

100 drivers (64 males, 36 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 22 and 70 years, with a mean of 34 years and standard deviation 11.3 years. 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.

Each participant encountered vehicles in the opposing lane. The passing gaps, which are the gaps between these vehicles, were defined by the time spacing between the two vehicles at the time the subject encounters the lead vehicle in the opposing lane as illustrated in Figure 2.

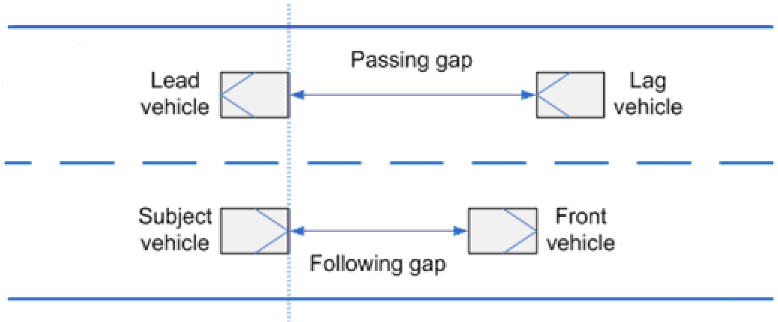

FIGURE 2: Definition of passing gap acceptance situation

It was further assumed that if the following distance between the subject vehicle and the vehicle in front in the same direction is larger than 30 meters (~1.8 seconds spacing) at the time the subject encounters the lead vehicle, the driver does not consider using the gap for passing. This value was chosen based on results reported by Hegeman et al. (2004) who found that the distances between passing vehicles and the vehicles in front at the start of the passing maneuver is distributed with mean 17.8 meters and standard deviation 9.8 meters and that in 92% of the passing maneuvers this distance was less than 30 meters.

4. MODEL FORMULATION

The data collected in the experiment described above was used to estimate a model of the decision whether to accept or reject passing gaps. The gap acceptance model is formulated as a binary choice decision: Drivers compare the available gap with an unobserved critical gap in order to either accept or reject the available gap:

$$Y_n(t) = \begin{cases} 1 & \text{if} \quad G_n(t) \geq G_n^{cr}(t) \\ 0 & \text{if} \quad G_n(t) < G_n^{cr}(t) \end{cases} \qquad (1)$$

Where $Y_n(t)$ is the choice indicator variable for driver n with value 1 if the gap is accepted and 0 otherwise; $G_n(t)$ is the available gap; and $G_n^{cr}(t)$ is the critical gap for driver n. Critical gaps are not directly observable, and so they are modeled as random variables with means that are a function of explanatory variables:

$$G_n^{cr}(t) = X_n(t)'\beta + \varepsilon_n(t) \tag{2}$$

Where $X_n(t)$ and β are vectors of explanatory variables and the corresponding parameters. $\varepsilon_n(t)$ is a random error term, which is assumed to follow a logistic distribution. Under this assumption, the gap acceptance process is formulated as a binary logit choice model. The resulting probability of accepting a given passing gap is given by:

$$P_n\left(accept\ gap\right) = \frac{1}{1+\exp\left[-\mu(G_n - X_n(t)'\beta)\right]} \tag{3}$$

Where μ is the scale parameter of the model, which is inversely proportional to the standard deviation of the critical gap distribution. In the model estimation, the coefficient of the available gap was normalized to be 1 and therefore the scale parameter μ could be estimated. This normalization assumes that gap acceptance probabilities increase when the available gap is larger.

5. MODEL ESTIMATION

A total of 9,953 passing gap observations were recorded in the experiment. 1,298 (13%) of these gaps were accepted, and the passing maneuvers were completed. Table 2 summarizes the estimation results for five different passing gap acceptance models. The models differ in the groups of variables that were included. Model 1 includes only variables that describe the traffic conditions. Model 2 adds the variable related to the road geometric design level. Models 3 and 4, in addition, take into account the driving styles score variables and drivers' socio-economic characteristics, respectively. Model 5 combines both these two groups of variables. In the table, values in parentheses are t-statistics.

TABLE 2: Estimation results for passing gap acceptance models

	Variable	**Model 1**	**Model 2**	**Model 3**	**Model 4**	**Model 5**
	Constant (sec.)	25.07 (13.02)	26.19 (13.57)	28.18 (13.65)	34.12 (16.07)	33.93 (15.28)
Traffic variables	Subject speed (km/hr)	-0.36 (-20.84)	-0.35 (-20.42)	-0.33 (-19.44)	-0.31 (-18.46)	-0.31 (-18.08)
	Following gap (sec.)	5.87 (12.61)	5.91 (12.70)	5.57 (11.90)	5.35 (11.73)	5.31 (11.49)
	Speed of lead vehicle (km/hr)	0.46 (17.48)	0.45 (17.42)	0.44 (17.02)	0.42 (16.59)	0.42 (16.52)
	Speed of vehicle on opposing lane (km/hr)	-0.12 (-6.50)	-0.13 (-6.77)	-0.13 (-6.98)	-0.15 (-7.84)	-0.15 (-7.89)
	Road geometry factor (Good= 1, Poor=0)		-2.31 (-6.49)	-2.35 (-6.62)	-2.41 (-6.83)	-2.42 (-6.87)
Driving styles	Angry and hostile			-0.55 (-3.54)		-0.26 (-1.58)
	Anxious			0.15 (0.69)		0.40 (1.77)
	Reckless and careless			-0.27 (-1.53)		0.15 (0.86)
Driver characteristics	Age 34 or under				-7.04 (-8.56)	-7.14 (-8.60)
	Age 35 to 49				-4.99 (-5.61)	-5.00 (-5.63)
	Gender (Male=1, Female=0)				-2.64 (-6.35)	-2.48 (-5.81)
	Parent (Yes=1, No=0)				0.31 (2.61)	0.29 (2.43)
	Drives under 1500 km per month (Yes=1, No=0)				0.98 (2.58)	1.03 (2.67)
	Cumulative distance (m.)	-5.40E-5 (-2.17)	-5.61E-5 (-2.28)	-5.12E-5 (-2.09)	-4.84E-5 (-1.99)	-4.61E-5 (-1.89)
	μ (scale parameter)	0.21 (35.15)	0.21 (35.20)	0.21 (35.22)	0.22 (35.22)	0.22 (35.20)
	Number of parameters	7	8	11	13	16
	Number of observations	9953	9953	9953	9953	9953
	Null log-likelihood	-6898.89	-6898.89	-6898.89	-6898.89	-6898.89
	Final log-likelihood	-2396.67	-2375.36	-2367.08	-2290.98	-2288.41
	Rho-square	0.653	0.656	0.657	0.668	0.668
	Adjusted Rho-square	0.652	0.655	0.655	0.666	0.666

Likelihood ratio tests were conducted in order to select among the alternative models. Table 3 summarizes the results of these tests. For example, the first test was on the null hypothesis that the addition of the road geometry factor in model 2 compared to Model 1 is statistically significant. The likelihood ratio test statistic value is 42.6 with 1 degree of freedom, which corresponds to rejecting model 1 and adopting model 2 with p-value< 0.0001. The same procedure was conducted among the other models suggested.

The test results support Model 4 as the best among the alternative models presented. This model includes socio-economic variables, but not the driving style variables. The result that both groups of variables are not jointly significant may be expected since the variables in these two groups are correlated. For example, a significant correlation (ρ=0.33) was found between drivers' ages and their angry and hostile driving style scores. Accordingly, the angry and hostile driving style variable significantly affects critical gaps in Model 3 that does not use age as an explanatory variable, but is not significant in Model 5 that does use the age variables.

TABLE 3: Summary of the likelihood ratio tests

Models	Likelihood ratio statistic	Degrees of Freedom	Test p-value	Selected Model
Model 1 vs. Model 2	42.62	1	<0.0001	Model 2
Model 2 vs. Model 3	16.56	3	0.0008	Model 3
Model 3 vs. Model 5	78.67	5	<0.0001	Model 5
Model 5 vs. Model 4	5.14	3	0.162	Model 4

Based on the estimation results of model 4, Figure 3 shows the impact of some of the explanatory variables on the probability of passing gap acceptance. In each of the four sub figures, one variable was varied while all other variables were fixed. The probabilities shown in the figure were calculated for a male driver, aged 35 to 49 with no children, and who drives more than 1500 km. per month. Unless varied the figures assumes that the available passing gap is 20 seconds, the speeds of the subject and the opposing vehicles are 85 km/hr, the speed of the lead vehicle is 60 km/hr, the following gap is 1.5 seconds, the road has a high design standard.

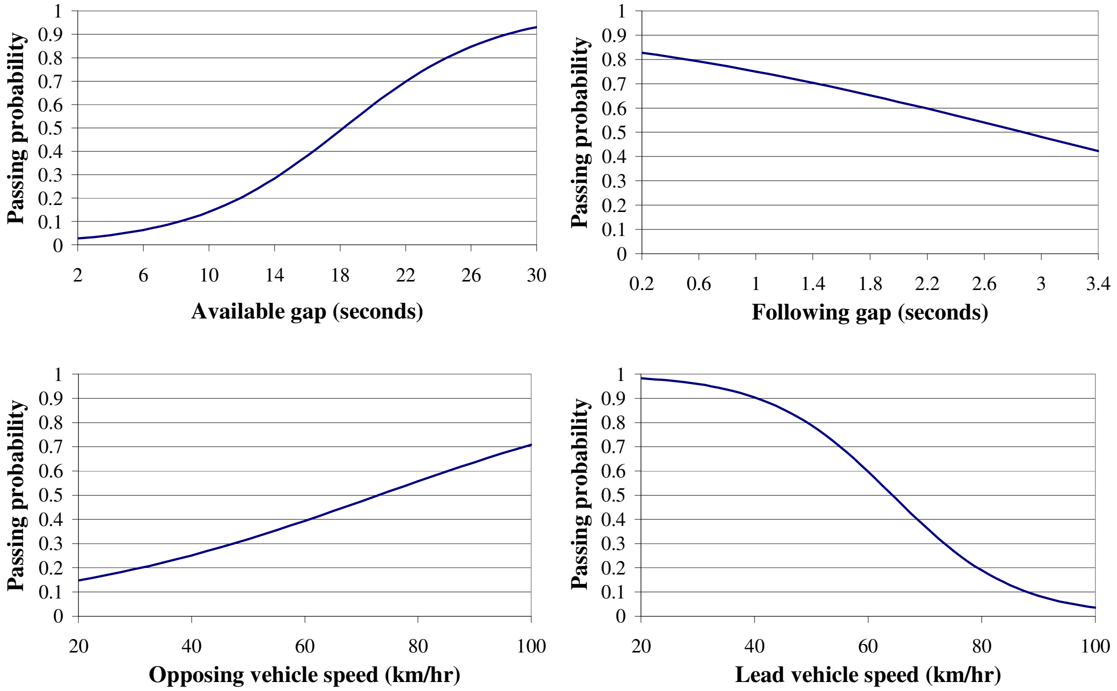

FIGURE 3: Impact of various explanatory variables on gap acceptance probabilities

The estimation results for the selected Model 4 show that passing gap acceptance decisions are affected the most by the variables related to the subject vehicle and the other relevant vehicles: the lead and the opposing vehicles. These variables include the size of the available gap, the speed of the subject vehicle and the following gap to the lead vehicle. Mean critical passing gaps decrease when the speed of the subject vehicle increases. This may be both because the completion of a passing maneuver requires less time and shorter distance and that the incentive for the subject to pass increases when its speed is higher. For similar reasons mean critical gaps increase when the speed of the lead vehicle increases and when the spacing from the lead vehicle increases, which make the maneuver more difficult to complete. In contrast, critical gaps decrease when the speed of the opposing vehicle increases. Noting that critical gaps are measured in time units, a higher speed of the opposing vehicle means that in terms of distance the critical gap increases. 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.

The road geometric design standards also affect critical gaps. As expected, critical gaps are smaller in roads with high design standards compared to those with lower standards. Individual infrastructure characteristics, such as lane width, shoulder width, curvature and side slope were not found significant, but only the overall design standards.

Critical passing gaps vary substantially with drivers' characteristics. They are significantly smaller for younger drivers compared to older ones, for males drivers compared to females, and for subjects without children compared to those that are parents. These results are consistent with previous studies that found that young and male drivers tend to behave more aggressively and take more risks (e.g. Evans 2004). The estimation results also show that drivers who drive more each month accept smaller passing gaps compared to drivers who drive less. The effect of the driving styles, as noted above, was not significant at the 95% confidence level and so was not retained in the final model. Nevertheless, in the models that incorporated these variables, critical passing gaps were lower for drivers that scored higher on the angry and hostile driving style and on the anxious driving style scales.

The collection of driving simulator data rather than real-world observations 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 in order to complete the task sooner. The cumulative distance variable, which is defined as the total distance the subject vehicle has driven from the beginning of the experiment to the measurement point, captures and corrects this effect. It has a statistically significant, but small, negative impact on critical gaps. This implies that critical gaps decrease as the experiment progresses. It should be noted that variables that capture drivers' impatience in the passing behavior itself, such as the time delay or number of rejected gaps since the subject began to consider passing the vehicle in front, were not significant, and therefore omitted from the models presented in Table 2.

6. SUMMARY AND CONCLUSIONS

Passing gap acceptance is an important driving behavior that has important implications on traffic flow and safety in two-lane rural roads. However, detailed data that can be used to explain passing behavior is difficult to collect in the real-world, partly because passing maneuvers may take place at any point on the road. In this study, data that was collected with an interactive driving simulator in a laboratory environment is used to develop a passing gap acceptance model. The model incorporates variables that capture both the impact of the attributes of the specific passing gap that the driver evaluates (e.g. passing gap size, speed of the subject vehicle and the following distance it keeps from the vehicle in front), the infrastructure quality of the specific road section and the personality characteristics of the driver (e.g. gender, age, kilometers driven per month, accident record). The results indicate that all these types of variables significantly affect passing behavior.

The developed model enhances the understanding of drivers' gap acceptance behavior on two-lane rural roads and the factors that affect passing decisions. There are several directions in which this work may be extended in order to strengthen and further validate the usefulness of the results. Among these are: (1) Investigation of the gap acceptance behavior in more diverse traffic and road geometry conditions, and testing of additional variables such as the impact of the vehicle types of the various vehicles involved; (2) Extension of the modeling framework to explicitly include the motivation to pass the vehicle in front, the possibility of aborted passing maneuvers, passing of multiple vehicles at once and so on; (3) Validation of the simulation results against data from the real-world to eliminate any biases resulting from the use of simulator observations; (4) Implementation of the gap acceptance model in traffic flow models, such as microscopic traffic simulation models, to validate their performance as predictors of macroscopic traffic flow characteristics and of traffic safety.

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