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Study of passing gap acceptance behavior using a driving simulator

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Abstract

This paper presents research to evaluate drivers' passing maneuvers on two-lane rural roads using data collected with STISIM, an interactive driving simulator. In addition to the observations of driving behavior obtained in the simulator experiments, drivers' socioeconomic characteristics and indicators of their driving style were collected using self-reported questionnaires. The participants were asked to drive a 9.5 km two-lane rural road section with no intersections. The positions and speeds of the subject vehicle and the other simulated vehicles were recorded at a resolution of 0.1 seconds. The data collected in the experiment was used to develop a model that explains drivers' passing decisions. The results indicate that the speed of the subject vehicle and its relations to the vehicle being passed are the most important factors affecting passing behavior. In addition, drivers' socio-demographic characteristics and driving styles also affect passing decisions.

Keywords – Passing, critical gap, gap acceptance, driving style, driving simulator

1. Introduction

Passing maneuvers in rural two-lane roads significantly affects road capacity, safety, and level of service [1]. This maneuver, which involves driving in the lane of the opposing traffic direction, is associated with an increase in the risk of a crash [2]. Studies using self report ratings indicate that most drivers are indeed aware that passing is a risky maneuver [3]. Thus, understanding of drivers` gap acceptance behavior on two-lane rural highways can significantly contribute to traffic analysis and safety considerations, level of service and traffic simulation models. However, as discussed in the next section, only limited research has been conducted to develop gap acceptance models for two-lane rural roads. The main purpose of this paper is to model drivers' gap-acceptance decision as a function of traffic, socio-demographic and driving style parameters. The paper describes a laboratory experiment, which consisted of a self-report questionnaire and a driving simulator session. Based on the data extracted from the questionnaire and the simulation experiment, a model of decision to undertake a passing maneuver was developed. .

The rest of the paper is organized as follows: Section 2 briefly presents studies concerning passing maneuvers. Section 3 describes the experiment methodology and data collection effort. Section 4 presents the dataset characteristics. Section 5 presents the formulation, specification and estimation of the gap acceptance model. Section 6 presents the conclusions and directions for further research.

2. Literature Review

Despite its importance, not many studies have been conducted on modeling passing gap acceptance behavior. Early studies in this area discussed drivers' perception of the required gaps for passing [4], [5], [6]. For example, Jones and Heimstra [4] studied the ability of drivers to estimate as closely as possible the last safe moment for passing a vehicle with another car approaching. Other studies focused on examining the major components of the passing process and factors which affect this process, such as the required sight distances [1], [7], [8], [9]. For example Polus et al. [1] studies 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. Other studies examined the influence of the speeds of the passing vehicle and the vehicle being passed on the tendency to undertake a passing maneuver. For example, Bar-Gera and Shinar [2] developed a driving simulator experiment to assess the differences in speed that prompt drivers to pass the lead vehicle. The simulator scenario did not include any traffic in the opposite direction and so gap acceptance was not assessed. Clarke et al. [10] analyzed 973 accident files and reported on the various ways in which inappropriate passing can lead to road accidents. Pollatschek and Polus [11] quantified driver's impatience during passing maneuvers. They found that the critical gap decreases with an increase in two-way hourly volume. In summary, little research has been conducted to develop models for passing gap acceptance behavior. In part this is due to the difficulties of observing passing maneuvers in the real world [12]. In this study a driving simulator was used in order to collect data on passing behavior. Various studies have shown that driving simulators can provide reliable observations of drivers' behaviors [13], [14], [15].

3. Experiment design

A laboratory experiment using the STISIM driving simulator [16] 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 (MDSI) developed by Taubman Ben-Ari et al. [17]. The MDSI is a 6-point scale, which consists of 44 items that are used to characterize four factors that represent various driving styles:

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, race in cars, pass other cars in no-passing zones, and drive while intoxicated, probably endangering themselves and others;
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, and
4. Patient and careful driving, which refers to planning ahead, attention, patience, politeness, and calmness while driving as well as obedience to traffic rules.

Factor scores were calculated for each respondent on each of these four driving styles.

Figure 1. Snapshot of the STISIM driving simulator scenario

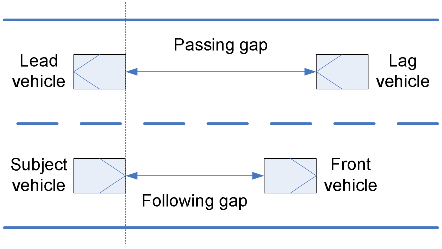

Figure 2. Definition of passing gap acceptance situation

In the simulator experiment participants were asked to drive along a 9.5 km two-lane rural highway segment with no intersections. Figure 1 shows a snapshot of the drivers' view of the section. The road section was designed without any grade and with a few curves. Lane and shoulder widths were 3.75 meters and 1.5 meters respectively. Day time and good weather conditions, which allow good visibility, were adopted in this scenario. The speed of all vehicles traveling in the same direction as the subject was constant at 60 km/hr. All vehicles traveling in the opposite direction were traveling at 70 km/hr. The posted speed limit was 90 km/hr. Headways between vehicles in the opposing direction were drawn from a truncated negative exponential distribution with a mean of 15 seconds. 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.

Thirty five (35) drivers (24 males, 11 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 50 years, with a mean of 32.1 years and standard deviation 6.9 years. All participants were students or employees at the Technion, who responded to advertisement of the experiment.

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 information, other variables of interest, such as the times and location of passing maneuvers, distances between vehicles and relative speeds were calculated.

Passing gaps are the gaps between vehicles in the opposing lane. They were measured by the distance between the two vehicles at the time the subject vehicle passed the first one, as illustrated in Figure 2.

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 headway), the driver does not consider passing the vehicle in front.

Table 1. Passing gaps summary statistics

Statistic	Number of gaps faced	Number of accepted gaps	Accepted passing gap (seconds)	Rejected passing gap (seconds)	Travel speed (km/hr)	Number of crashes
Mean	40.1	9.5	19.5	15.5	77.7	0.23
Standard	15.2	5.1	3.7	4.2	12.9	0.43
Min	11	0	9.9	9.6	58.8	0.00
Max	76	19	24.0	24.0	107.1	1.00
Median	36.5	10.5	20.9	14.2	75.4	0.00

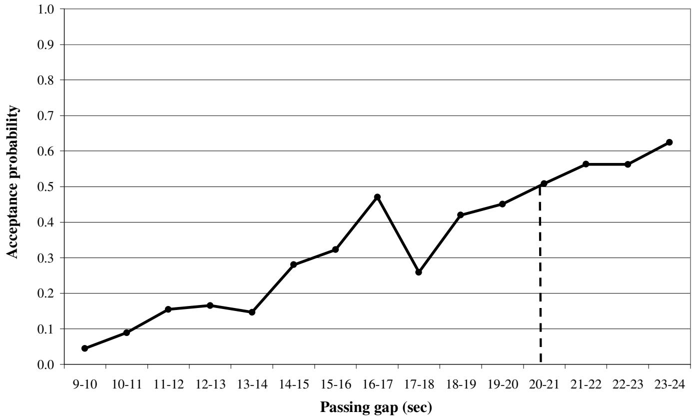

Figure 3. Passing gap acceptance and rejection probabilities

4. Dataset characteristics

A total of 1359 passing gap observations were recorded in the experiment. 432 of these gaps were accepted, and the passing maneuvers completed. Table 1 presents summary statistics for important variables related to these passing gaps. Note that all participants drove the same scenario. The variation in the number of gaps that they evaluated is a result of differences in the travel speeds and following headways that drivers chose, as shown in the table. The travel speed reported in the table is the average over the entire section. The total number of car crashes that occurred in the simulator experiment was 8 for all 35 drivers. Out of these crashes 4 were head-on crashes while passing and 4 front-back crashes, in which drivers did not keep a safe distance from the leading vehicle. This indicates on willingness to take higher risk compared to real driving, either due to under-estimation of crash risks or indifference to the crash consequences in the simulator environment.

Figure 3 shows the probabilities of passing gap acceptance as a function of the passing gap size. The acceptance probabilities are estimated by the fraction of gaps of a particular size that were accepted. These probabilities increase as the gap size increases. The correlation between the passing gap size and the passing decision is 0.396 (p=0.01). The critical passing gap is defined as the gap size where the probability of acceptance is equal to 50%, which is about 21 seconds in this data. Table 2 presents the pearson correlations among the drivers' performance variables that were recorded in the simulator and the driving style scores in the MDSI scale. The numbers in paranthesis are the two-tail significance levels of the correlations. Correlations that are significant at the 0.05 level are also marked in bold. In the table, NP is the number of Passing maneuvers the drivers completed, CPG is the critical passing gap for the driver, which was estimated based only on the observations of that driver. AHDS, RCDS, PCDS and ADS are the angry and hostile, reckless and careless, patient and careful and anxious driving Styles, respectively. The age variable is a binary variable, which takes the value 1 for drivers that are 35 years old or younger and 0 for older drivers.

Table 2. Significant correlations between driving perfomance in the simulator and driving styles

	Age	**Gender**	**Speed**	**NP**	**CPG**	**AHDS**	**RCDS**	**PCDS**	**ADS**
Age	1								
Gender	0.04 (0.84)	1							
Speed	0.21 (0.21)	**0.33** **(0.05)**	1						
NP	0.19 (0.27)	**0.34** **(0.05)**	**0.97** **(0.00)**	1					
CPG	0.10 (0.57)	0.02 (0.92)	**-0.76** **(0.00)**	**-0.75** **(0.00)**	1				
AHDS	**0.33** **(0.05)**	0.32 (0.06)	0.01 (0.96)	0.15 (0.38)	0.25 (0.16)	1			
RCDS	0.24 (0.16)	0.23 (0.18)	**0.36** **(0.03)**	**0.32** **(0.05)**	-0.31 (0.08)	-0.06 (0.74)	1		
PCDS	0.03 (0.86)	-0.19 (0.26)	0.02 (0.93)	-0.01 (0.94)	-0.02 (0.89)	0.15 (0.38)	-0.10 (0.56)	1	
ADS	-0.04 (0.81)	0.31 (0.07)	-0.19 (0.27)	-0.15 (0.37)	0.13 (0.48)	-0.01 (0.93)	-0.08 (0.64)	-0.03 (0.84)	1

No significant correlations were found between this variable and the driving performence measures. A significant positive correlation was found between this age indicator and the angry and hostile driving style, which indicates that young drivers tend to be more angry and hostile in driving. Other driving styles had no significant correlations with age.

The gender variable (male=1, female=0) had significant correlations with both the speed and the number of completed passing maneuvers, indicating that male drivers tend to complete more passing maneuvers and to drive faster compared to female drivers. The correlation between gender and both the angry and hostile and the anxious style were close to significant.

The correaltions among the performence measures collected in the simulator are significant, as might be expected. Participants who drove faster also completed more passing maneuvers and their estimated critical passing gaps were shorter. The maximum likelihood method was adopted for this purpose while the lognormal distribution was assumed.

The speed and number of completed passing maneuvers and to a lesser extent also the critical gaps were significantly correlated with higher scores in the reckless and careless driving style scale.

5. Gap acceptance model

A passing gap acceptance model was developed by taking into account attributes of the passing gap and the driver characteristics. The gap acceptance model was formulated as a binary choice problem. Drivers compare the available gap with an unobserved critical gap and decide whether to accept or reject it:

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

where $Y_n(t)$ is a choice indicator variable with value 1 if the gap is accepted and zero otherwise. $G_n(t)$ and $G_n^{cr}(t)$ are the available passing gap and the critical passing gap, respectively.

Table 3. Passing gap acceptance model estimation results

Parameter	Value	t-statistic
Critical gap constant	33.02	9.31
Following distance (meters)	0.82	11.48
Subject speed (m./sec)	-1.79	-11.42
Anxious driving style	0.83	1.88
Patient and careful driving style	1.41	2.76
Age up to 35	-2.32	-2.58
μ (scale parameter)	0.28	12.26
No. parameters 7, No. observations 1359 Null log-likelihood -942.0 Final log-likelihood -400.2 Rho-square 0.575 Adjusted rho-square 0.567		

Critical gaps 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, respectively. $\varepsilon_n(t)$ is a random error term, which is assumed to follow a logistic distribution. Under this assumption the gap acceptance problem is formulated as a binary logit choice model. 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. Table 3 summarizes the estimation results for the passing gap acceptance model. Figure 4 shows the impact of the various explanatory variables in the model on the probability of passing gap acceptance. Unless varied, Figure 4 assumes that the available passing gap is 20 seconds, the subject speed is 70 km/hr, the following distance is 15 meters, the driver is older than 35 years and scored 3 points on both the patient and careful and anxious driving style scales.

Critical passing gaps and consequently passing gap acceptance decisions are affected by variables that describe the situation the driver is faced with (in addition to the size of the available gap): Acceptance probabilities increase with the speed of the subject vehicle and decrease with the following distance from the vehicle in front. The characteristics of the driver also affect passing gap acceptance behavior. Passing critical gaps increase with the driver's scores on the anxious driving style and the patient and careful driving style scales, as defined in the MDSI scale [17]. This result indicates that more anxious and more patient and careful drivers require larger critical gaps, and so are less likely to undertake passing maneuvers. The two other driving styles defined in the MDSI (i.e. reckless and careless driving and angry and hostile driving) did not have any significant impact on critical gaps. Finally, the critical passing gaps for drivers that are 35 years old or younger were significantly smaller compared to those of older drivers. This result is consistent with previous studies, which indicate that young drivers tend to take more risks in driving compared to older drivers. The impact of other socio-demographic variables, such as gender, was not statistically significant. This may be partly due to insufficient numbers of drivers and variability between these drivers (e.g. only 11 female drivers in the sample).

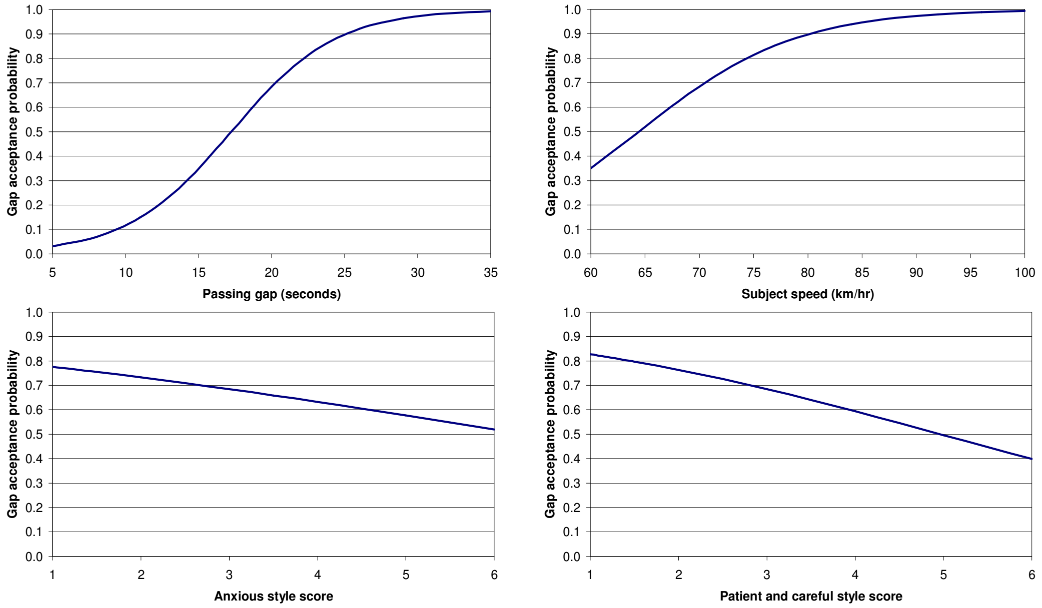

Figure 4. Probability to pass as a function of the passing gap size and the subject speed

6. Conclusion

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) and the personality and socio-demographic characteristics of the driver (e.g. driving style scores and age). The results indicate that both types of variables affect passing behavior. The developed model enhances the understanding of drivers' behavior on two-lane rural roads and the factors that affect their decision to pass slow vehicles.

This model has potential benefits to traffic and safety aspects, level of service and traffic simulation models. However, there are several directions in which this work could be extended in order to strengthen the results and validate the usefulness of the results:

1. Analysis of a larger and more diverse sample of drivers;
2. Investigation of the impact on critical gaps of varying road geometry and traffic conditions (e.g. traffic volumes in the two traffic directions, speeds of the front vehicle);
3. Generalization of the modeling framework to include the motivation to pass the vehicle in front, the possibility of aborted passing maneuvers, passing of multiple vehicles at once and other similar behaviors: and
4. Implementation of the gap acceptance model in traffic prediction tools to validate their performance as predictors of macroscopic traffic flow characteristics and of traffic safety.

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