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**Evaluation of Dynamic Passing Gap Acceptance on
Two-Lane Highways Using Field Data**

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ABSTRACT

Gap availability is an important element of safe passing on two-lane highways. Time gaps are used to determine passing behaviour based on human factors. In this paper, the decision whether to accept or reject an available passing gap is modelled using logistic regression technique that included driver characteristics (age and experience) and the gap size. Field studies were conducted to collect experimental data regarding passing driver behaviour. The data were collected using Dual Camera Car DVRs and a GPS data logger device that records the instantaneous speed and position of the three vehicles involved in the passing maneuver: passing vehicle, impeding vehicle, and opposing vehicle. Regression models that include driver age and gender (required as input to the gap acceptance model) were established for initial passing time, starting gap, ending gap, and time to collision. The gap acceptance model was implemented in SIMULINK and the results revealed that driver characteristics significantly affect gap acceptance decisions.

1. Introduction

Adequate passing sight distance (PSD) is necessary to ensure the safety of passing drivers on two-lane highways. The passing maneuver can be completed when there is a safe clearance distance between the passing and incoming vehicles and the driver can safely return to the right lane. When conducting passing maneuvers, there is always a risk of head-on collisions. In Canada, passing (head-on) collisions accounted for approximately 30% of all collisions reported in 2010 (Rural Road Safety in Canada 2010). In the USA, head-on collisions accounted for approximately 20% of fatal collisions occurring on rural two-lane highways and passing is one of the primary causes of these types of collisions (Persaud et al. 2004). Passing maneuvers are also

Canadian Journal of Civil Engineering

51 regarded as one of the most difficult maneuvers on rural two-lane highways due to the changes in
52 speed and position necessary for safe completion (Mcknight et al. 1970). Therefore, the design of
53 adequate PSD for two-lane highways is critical (Farah 2013).

54 Despite the importance of this issue, a few studies have attempted to model passing
55 behaviour. Several researchers have developed analytical models that depend on motion
56 equations to ascertain the required sight distances (AASHTO 1994; Polus and Frischer 2000).
57 Some researchers have used macroscopic traffic characteristics to predict the number and
58 frequency of passing maneuvers (Hegeman 2004) while others have focused on the impact of
59 impatience on critical passing gaps (Pollatschek and Polus 2005). Judgment errors regarding
60 distance and speed (of both the passing and opposing vehicles) and insufficient clear sight
61 distance can contribute to passing failure (Clarke et al. 1998). In addition, the variables that
62 influence the mean critical gaps were not accounted for in earlier studies that estimated critical
63 passing gap distributions (Miller and Pretty 1968).

64 There are several issues with the observation of driving behaviour during passing
65 maneuvers. First, the passing maneuvers can occur anywhere along the passing zone. Second,
66 previous field studies do not allow researchers to control the explanatory variables and do not
67 provide information about driver characteristics. Jenkins and Rilett (2004) used driving
68 simulators to collect data and developed a classification system for passing maneuvers, while
69 Bar-Gera and Shinar (2005) used driving simulators to examine the effect of speed differences
70 between passing and impeding vehicles on the driver's desire to pass. However, these studies did
71 not consider opposing vehicles and passing feasibility (such as gap acceptance characteristics).
72 Farah et al. (2009) and Farah (2013) developed a model of passing gap acceptance that considers
73 the impact of traffic conditions, road geometry, and driver characteristics. However, the model

was based on driving simulator data and didn't use actual field data. Passing is usually modeled as a binary decision, where the driver either accepts or rejects an available passing gap in the opposing lane.

The purpose of this paper is to examine the effect of driver characteristics on passing maneuvers and to develop a binary model for gap acceptance using field data. Regression models were developed for relevant parameters, including initial passing time, starting gap, ending gap, and time to collision, which are necessary elements of time gap length. The proposed model was implemented in SIMULINK. The following sections describe the data collection and analysis, passing gap acceptance model, and parameter estimation. The simulation and application examples are then presented, followed by a comparison between the results of field studies, computer simulation, and driving simulator.

2. Data Collection and Analysis

2.1 Variables and Equipment

The elements of the passing maneuver are shown in Fig. 1. The critical point is defined as the point when the passing vehicle is abreast to the impeding vehicle. The starting gap time, $G_s(t)$, is defined as the time from the moment a passing vehicle begins to cross the centreline towards the left lane until it reaches the critical point (s). The ending gap time, $G_e(t)$, is defined as the time from the moment a passing vehicle moves from the critical point to the start of crossing the centre dashed line and goes back to the right lane (s). The total gap time, $G_T(t)$, is defined as the time from the moment the passing vehicle begins to cross the centreline towards the left lane until the moment it begins to cross the centerline and returns to the right lane (s). The transition time, $G_o(t)$, is the time from the crossing of the road centerline by the passing vehicle until it

Canadian Journal of Civil Engineering

completely returns to the right lane. The time to collision, TTC , is defined as the time between the passing and opposing vehicles when the passing vehicle completes the pass and returns to the right lane (s).

Using field data, the parameters $G_s(t)$, $G_e(t)$, $G_o(t)$, and TTC were recorded using a smartphone by pressing “Start” and “Lap” when analyzing the data of the video camera for the passing vehicles. A GPS data logger device (Holux RCV-3000) installed on-board the passing, impeding, and opposing vehicles was used to record the position (latitude, longitude, and altitude) and speed of the vehicles at 1-s intervals. The device measures the speed with a precision of 0.1 m/s (0.36 km/h) (Holux Technology 2014). Since this system is normally applied to passing zones on two-lane highways with speed limits of 80 km/h, the relative error is expected to be insignificant.

2.2 Data Collection Process

Field data were collected at four passing zones on a two-lane highway at three sites: Abu Dhabi and Sharjah in UAE and Muscat in Oman. The lengths of the passing zones ranged from 300 m to 1200 m. The lane width for each direction was between 3.5 m and 4 m. All data were collected during off-peak periods on roads with good pavement conditions and good weather. The traffic flow rates ranged from 100 to 250 vehicles/hr. Sites with low flow rates were selected because sites with higher flow rates had limited passing maneuvers, according to research conducted by Harwood et al. (2010). The speed limit on the highway sites was 80 km/hr. Travel time and speed for each vehicle were recorded using HD in-vehicle video cameras and GPS data loggers. The number of passing maneuvers executed at all passing zones was 105. The sample was randomly selected from each group of passing drivers and included 17 male and 8 female drivers

between the ages of 20 and 63 years old. The age mean was 34 and the standard deviation was 13.

The passing scenarios were designed using proper schedules that were given to the drivers of the passing, impeding, and opposing vehicles. The schedule showed the time when the driver should begin driving and was designed to create passing maneuver situations. The impeding driver began driving earlier than the opposing and passing drivers. The driver of the impeding vehicle was instructed to drive slower than the posted speed limit, while the drivers of the passing and opposing vehicles were instructed to drive at the posted speed limit. The individual drivers were unaware that there were two other drivers (with equipped vehicles) on the road to ensure that there was no impact on their behaviour.

The actual field data were collected using a total of 25 drivers who repeatedly drove on the highway according to the schedule. However, the situation involving the combination of the passing, impeding, and opposing equipped vehicles occurred only 123 times. There were many instances when the passing driver does not face an impeding equipped vehicle. The information about driver characteristics were collected using a questionnaire completed by each participant before the study commenced.

2.3 Variability of PSD Parameters

Table 1 shows the passing maneuver parameters of the field data and their statistical characteristics. The table shows the mean (μ), standard deviation (SD), and a summary of the statistical measures for all 105 completed passing maneuvers. The passing maneuver parameters are consistent with those obtained in previous research conducted by AASHTO (2004) and Jenkins and Rilett (2005). When analyzing the passing maneuver parameters using AT RISK

software (Palisade Corporation 2016), the distribution is generated based on the goodness-of-fit statistics of Chi-Square and Kolmogorov-Smirnov. For each distribution specified, the program tries to find a set of parameters that best fit the observed data. The data for the time of initial maneuver (t_I) followed a normal distribution shape. The data for the time gap length ($ln GL$), speed differential (m), and speed of passing vehicle (V_p) followed a Weibull distribution. Meanwhile, the data for the initial distance between passing and opposing vehicles (D) followed a lognormal distribution, as shown in Fig. 2.

The passing vehicle speed, $V_p = 23.5$ m/s, suggested by AASHTO (2004), is consistent with the 95th percentile speed of the observed field data. The correlation coefficient between the speed differential (m) and the speed of the passing vehicle, ρ_{mv} , was 0.691. and that between TTC and speed reduction, ρ_{tv} , was 0.236. The positive signs of these coefficient are logical since m and TTC are expected to increase as the speed of the passing vehicle increases. Information regarding the mean (μ), standard deviation (σ), and probability distribution of various parameters are required for Simulink model and are presented in Table 1. The results for the statistical significance (95% confidence level) involving the mean of the passing maneuver parameters are also shown in the table.

3. Passing Gap Acceptance Model

The passing gap acceptance model was estimated using field data to evaluate passing driver behaviour. This study focused on the decision of whether or not to pass a slow moving vehicle. In making this choice, the passing vehicle needs to consider the available passing gaps. The method used in this study is similar to that used by Farah (2013). However, the present study is based on actual driving data instead of driving simulator data. Mathematically, the time gap is

Canadian Journal of Civil Engineering

166 calculated by dividing the distance between passing and opposing vehicles by the sum of their
 167 speeds.

168 The completion of passing maneuvers regarding the decision of whether to accept or
 169 reject an available passing gap is modeled. The logistic regression technique was used to
 170 calculate the probability of completing a passing maneuver. The generalized linear model (GLM)
 171 is used for this purpose (Kutner et al. 2004; Miles and Shevlin 2001). Let the binary dependent
 172 variable (Y) be defined as follows:

$$173 \quad Y = \begin{cases} 1, & \text{Accepted Gap} \\ 0, & \text{Rejected Gap} \end{cases} \quad (1)$$

174 where $p(Y=1/X_i) = \pi$ and $p(Y=0/X_i) = (1-\pi)$ represent the probabilities of accepted and rejected
 175 gaps, respectively, conditional on a vector of the independent variables X_i . The logistic
 176 regression model equation is obtained as follows:

$$177 \quad \text{Logit}\left(\frac{\pi}{1-\pi}\right) = \beta_0 + \beta_1 X_1 + \dots + \beta_n X_n \quad (2)$$

178 where X_i = independent variable i and β_i = coefficient of the independent variable i . The
 179 coefficients of the logistic regression model can be obtained from the maximum likelihood
 180 estimation method using statistical software implements GLM applications (Farah 2016; Kutner
 181 et al. 2004). The probability of an acceptable passing gap conditional on a vector of the
 182 independent variables X_i , $p(\text{pass})$, can be written as follows:

$$183 \quad p(Y = 1 / X_i) = \frac{\exp(\beta_0 + \beta_1 X_1 + \dots + \beta_n X_n)}{1 + \exp(\beta_0 + \beta_1 X_1 + \dots + \beta_n X_n)} \quad (3)$$

184 The expected probability of a passing gap should be larger than 0.5 (Lobo et al. 2011). The use
 185 of Eq. (3), after calibration using field data, allows for estimating the effect of each explanatory
 186 variable on the probability that a driver will accept or reject the passing gap. Fig. 3 illustrates the

logic of the passing gap acceptance model. The gap acceptance parameters were driver age, driving experience, and gap size. The estimated latent variable was as follows:

$$Gp = -0.632 - 0.006 \text{ Age} + 0.008 \text{ Exp} + 0.560 \ln(GL) \tag{4}$$

where Gp = latent variable related to the observed independent variables, Exp = driving experience of passing driver (years), and $\ln(GL)$ = natural logarithm of gap length (s). The estimated coefficients and goodness of fit for the model were based on the field data collected. The primary factor was gap acceptance, which is consistent with the findings obtained in the majority of previous studies. The results support the hypothesis that drivers make decisions that are dependent on the observed of passing driver characteristics. The results revealed that the estimated model was considerably significant. The model distribution is normal, Pearson Chi-Square is 9.3, and Log Likelihood is -15.8. The standard error of Age , Exp , and $\ln(PT)$ are 0.005, 0.007, and 0.077, respectively. The respective Wald Chi-Square are 1.01, 1.30, and 72.8. The scale is 0.2752 with a standard error of 0.018.

With the latent variable, G_p , the conditional probability that a driver will perform a passing maneuver (passing gap acceptance, $Y = 1$) is determined using Eq. (3) which is larger than 0.5 and consistent with previous research conducted by Lobo et al. (2011). The gap length of Eq. (4) was obtained using the following equation:

$$GL = t_l + G_s + G_e + G_o + TTC \tag{5}$$

where t_l = initial passing time (s), G_s = starting gap time (s), G_e = ending gap time (s), and TTC = time to collision (s). The estimation of these parameters is presented in the following section.

4. Parameters Estimation

Canadian Journal of Civil Engineering

Using the collected field data, linear regression models for t_l , G_s , G_e , and TTC were developed using SAS software (SAS 2015). The repeated measures ANOVA revealed the significant variables that affect these parameters during different passing maneuvers. Several variable combinations were tried to develop the best regression models. The estimated models for t_l , G_s , G_e , and TTC were as follows,

$$t_l = 3.810 + 0.100 \text{ Gender} + 0.021 \text{ Age} - 0.025 \text{ Exp} - 0.020 \text{ Awh} - 0.036 m \quad (6)$$

$$G_s = 2.646 + 1.964 \text{ Gender} + 0.213 \text{ Age} - 0.244 \text{ Exp} - 0.117 \text{ Awh} - 0.245 m \quad (7)$$

$$G_e = 2.324 + 1.003 \text{ Gender} + 0.033 \text{ Age} - 0.049 \text{ Exp} - 0.054 \text{ Awh} + 0.003 df \quad (8)$$

$$TTC = 15.751 + 0.235 \text{ Gender} - 0.125 \text{ Age} + 0.062 \text{ Exp} + 0.109 \text{ Awh} - 0.482 V_o \quad (9)$$

where Gender = passing driver gender (0 for males and 1 for females), Age = passing driver age (years), Exp = passing driver experience (years), Awh = passing driver weekly driving hours (hrs), m = speed difference (m/s), df = distance headway between the passing and opposing vehicles when the passing vehicle reached the critical point (m), and V_o = the opposing vehicle speed (m/s). The statistical characteristics of the model variables are presented in Table 2.

For the initial passing time parameter of Eq. (6), the model considered the initial time of the passing driver to ensure acceptable performance. To obtain precise measurements of this time, field data were collected using different drivers selected from various countries. The initial time was then measured from the moment the driver began to react and initiate the passing maneuver. The mean of the initial time was 3.6 s and the standard deviation was 0.6 s. 95% of the observations were less than 4.5 s. The value 3.6 s could therefore be used in PSD analysis.

There is a reasonable explanation for the choice of the parameters illustrated in the regression models. For t_l , G_s , and G_e , a positive sign for the gender parameter indicates that female drivers take a longer time than male drivers under similar conditions. A positive sign for

Age indicates that the gap time will increase with age. A negative sign for *Exp* and *Awh* indicates gap time decreases as experience and average weekly hours increase, which is consistent with the results of previous research (Mehmood and Easa 2009). For the *TTC* model, a negative sign for V_o is logical because *TTC* is expected to increase as the speed of the opposing vehicle decreases, which is consistent with the results of Jenkins and Rilett (2005).

5. Simulink Implementation

Simulink was used in this research because it demonstrated high efficiency of model development. The simulation and model-based design are provided using a block diagram environment that is extremely useful for multi-domain system elaboration. The structure of the Simulink model is shown in Fig. 3.

5.1 Model Description

Although the vehicle model allows only two-dimensional (2D) simulation, the results ensure an adequate reflection of the vehicle's maneuvering process. The generalized Simulink-model of 2D vehicle dynamics can be adjusted for any single vehicle including geometric, physical, and design features. The input data from field studies for Gap Length (GL) included the following: (1) passing vehicle's initial speed, (2) initial distance between passing and opposing vehicles, (3) initial acceleration of the opposing vehicle, (4) gender, age, driving experience, and average weekly driving hours of the passing driver, (5) number of lanes, lane width, and distance headway. The Simulink model can randomize the variables of regression models, which are based on probability distributions established from the field data (Table 1 and Fig. 2). This technique was used to provide the sample variability and was accomplished by the addition of

Canadian Journal of Civil Engineering

MATLAB-code to Simulink-model. Thus, the adjusted Simulink model can be used independently for estimating the required gap length GL .

257

5.2 Vehicle 2D-Dynamics Model

A Simulink model based on 2D vehicle dynamics (steerability) was developed to implement different passing scenarios on a two-lane highway. The basis of a single unit vehicle (SUV) model is the 2D steerability block in which all necessary components are implemented by the Simulink library. Each vehicle is described by a system of ordinary differential equations that are entered in the vehicle universal block, given by

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$$\begin{cases} m \delta_r \left(\frac{dV_{Cx}}{dt} - \frac{d\phi}{dt} V_{Cy} \right) = \sum F_x^{(e)} \\ m \left(\frac{dV_{Cy}}{dt} + \frac{d\phi}{dt} V_{Cx} \right) = \sum F_y^{(e)} \\ I \frac{d^2\phi}{dt^2} = \sum M_z \end{cases} \quad \begin{pmatrix} \frac{dV_{Cx}}{dt} \\ \frac{dV_{Cy}}{dt} \\ \frac{d\omega}{dt} \end{pmatrix} = \begin{pmatrix} \frac{I}{m \delta_r} & 0 & 0 \\ 0 & \frac{I}{m} & 0 \\ 0 & 0 & \frac{I}{I} \end{pmatrix} \begin{pmatrix} \sum F_x^{(e)} \\ \sum F_y^{(e)} \\ \sum M_c \end{pmatrix} + \underbrace{\frac{d\phi}{dt}}_{\omega} \begin{pmatrix} V_{Cy} \\ -V_{Cx} \\ 0 \end{pmatrix} \quad (10)$$

The primary feature of the proposed SUV model is the four-point road contact (as opposed to the bicycle models that are still widely used). The distribution of vertical forces on wheels (including longitudinal and lateral deviations), which are the most influential factors in the tire slip process, is provided. This distribution accounts for the effect of inertia pseudo-forces in a vehicle's mass center. The model uses a non-linear approximation of tire-road contact depending on the degree of adhesion. The steering axel-angle distribution is represented functionally as a result of the steering trapezoid's design optimization.

The system of dynamics equations Eq. (10) is represented by longitudinal, transversal, and rotational dynamics relative to vehicle local coordinate system. m represents the vehicle

Canadian Journal of Civil Engineering

mass, I represents the moment of inertia relative to axis OZ , V_{Cx} and V_{Cy} represent the velocities along the axes of the local coordinate system associated with mass center C , δ_r represents the coefficient that takes into account the inertia of the transmission's rotating masses, ϕ represents the angle of the vehicle's rotation around axis OZ , and $F_x^{(e)}$, $F_y^{(e)}$, M_z signify the generalized external force factors along the x and y axes and around z , respectively.

The Simulink model can be customized for any vehicle and takes into account the design, physical properties, and geometric properties of the vehicle. The simplest object is shown in Fig. 4, which allows for the combination of several car-models in one simulation scenario to reflect overtaking processes on two-lane highways. The basis of a single vehicle model, shown in Fig. 4(a), is block 1, where all necessary 2D-steerability components are implemented via the Simulink library. Blocks 2 and 3 are vectors that transmit initial positions (plane location and yaw rotation) and velocities (longitudinal, lateral, and yaw rate) according to degrees of freedom. Block 4 allows for the adjustment of the traction dynamics by means of the desired course velocity, and the current steering wheel angle is provided through input port 5. The outputs of block 1 are as follows: into port 6 - accelerations (longitudinal and lateral) in the vehicle's local coordinate system; into port 7 - velocities (longitudinal and lateral); into port 8 - all absolute displacements relative to the global coordinate system; into port 9 - steering wheel turning angles. Subsystem 10 sets the initial conditions of motion and control laws, and subsystem 11 obtains graphical representations of solutions. The model makes it possible to start an animation script that visually reflects the realism of the simulation.

5.3 Distance Headway Parameter

The PSD length is specified before assigning the location of the three vehicles. The Pitts car-following model can be used to calculate the minimum headway between the passing vehicle and the impeding vehicle (Halati et al. 1997). The minimum distance assumes that the passing vehicle is trying to narrow the distance between the passing and impeding vehicles before initiating a passing maneuver. The following formula was used to calculate the distance headway that is required between the two vehicles:

$$d_{l-2} = L_i + 10 + kV_p + bk(V_i - V_p)^2 \quad (11)$$

where d_{l-2} = space headway between the impeding and passing vehicles (from the front bumper to the front bumper), L_i = length of the impeding vehicle, and V_i and V_p = speed of the impeding and passing vehicles, respectively, b = calibration constant that is defined as 0.1 (when $V_p > V_i$) or 0 otherwise, and k = driver sensitivity factor for the passing vehicle. In the Pitts car-following model, the default values for the driver sensitivity factor range between 0.6 s and 1.5 s. At lower values, the behaviour becomes more aggressive and the following vehicles maintain a smaller distance headway. In this paper, the sensitivity for the passing driver can be captured through the variable k . The values for k are randomly selected from a uniform distribution, similar to the method used by El Khoury and Hobeika (2012).

5.4 Decision Making for Passing Gap Model

Vehicle control depends on the driver's subjective assessment of the road situation, as depicted in Fig. 5. The State-flow chart software provides the steering wheel angle as the output signal S . The decisive maneuver is composed of the four simplest combinations, which are executed by state blocks S0, S1, S2, S3, and S4. Therefore, the handling algorithm creates the control signal

Canadian Journal of Civil Engineering

318 S, which is changed functionally according to the current state. Driving modeling was done using
319 the PID-controller, which is well known in automation theory. The PID-controller forms the
320 output control signal from two input signals, which are the desired and actual steering angles.
321 The PID function compensates for the difference between the steering signal input (discussion of
322 gap acceptance) and the current calculated angle of the steering wheel.

323 The actual direction is defined by the current yaw angle ϕ_i ; and the theoretical direction
324 is calculated as a value of the angle deviation, which is a derivative and described by Hermit
325 polynomials on the basis length L from initial position x_0 . The chart operates as follows: When
326 the default initial state S0 is accepted, the zero-output signal S is provided. This corresponds to a
327 straight-ahead movement without any action on the steering wheel. When the input variable
328 *decision* to accept the passing gap (corresponding to Eq. (1)) becomes logical 1, the transition to
329 state S1 is carried out. The variable *decision* is tied with parameter π (corresponding to Eq. (2))
330 that estimates the probability of passage using Eq. (3). During the execution of state S1, the
331 passing vehicle is changing locations and moving toward the left lane. The transition from state
332 S1 signifies a switch to state S2 (further rectilinear motion).

333 In this case, the side displacement on the base length L will be completed. State S3 is
334 equivalent to state S1, but provides a negative sign for signal S to return the passing vehicle to
335 the right lane. When a transition from state S2 to state S3 is being executed, the passing vehicle
336 continues in a straight line until the critical point is reached. After that, state S3 provides the
337 signal for the vehicle to return to the right lane. State S4 then provides the signal to continue
338 moving in a straight line. The parameters t_1 , G_s , and G_e are used to arrange the conditions of
339 transitions between states. During these time intervals the passing vehicle is changing its
340 transversal position and lane.

5.5 Application of Simulink

An application example of one loop is provided in this section to illustrate the methodology for distance headway (d_{l-2}) and gap length (GL) that is used for passenger vehicles. To illustrate the uniqueness of the overtaking conditions and the relative vehicles disposition on rural two-lane highways, for each new simulation before calculations, random realizations of model parameters are generated according to the distributions established from field data. The input field data for the passing vehicle included the following: initial speed of 22.2 m/s, initial distance of 460.1 m, initial acceleration of the opposing vehicle of 0.51 m/s^2 , gender (female = 1), age of 34.8 years, driving experience of 13.9 years and average weekly driving hours of 17.8 hrs for the passing driver, and number of lanes of 2, lane width of 3.75 m, and design speed of 22.22 m/s.

Fig. 6 shows the kinematic characteristics of a passing vehicle during an overtaking procedure, allowing for a qualitative assessment of the adequacy of the virtual experiment simulation. The first curve represents the longitudinal acceleration of the vehicle's mass center (Fig. 6(a), blue colour). This curve represents the power unit's ability to realize the traction force depending on the adhesion with the road surface. The results indicate that the passing vehicle accelerates uniformly before transitioning into the opposing lane and shortening the distance to the impending vehicle. The acceleration remains constant after the passing vehicle enters the opposing lane, corresponding to vehicle velocity increments of the value Δv_{pl} .

The speed increases during overtaking and decreases once the critical point is reached. The lateral acceleration (Fig. 6(a), red colour) best demonstrates the model's ability to represent vehicle dynamics. The absolute value of the lateral acceleration does not exceed 4.5 m/s^2 during the maneuver. The peak values of the lateral acceleration correspond to moments of motion trajectory curvature changes, when lateral reactions reach the highest values. The inertia of

365 model dynamics during the transient process can be seen through the delay of the stabilization
366 mode.

367 The next curve (Fig. 6(b), magenta colour) represents the passing vehicle's displacements
368 on road lanes. Starting offset corresponds to the driver's *decision to accept the passing gap*,
369 which correlates with the passing gap model. There is then a transition process to the middle of
370 the opposing traffic lane which occurs according to the positive logical value of the parameter
371 *decision*. Overtaking is done while maintaining a steady position in the opposing lane, and a
372 sharper movement while completing the process and returning to the original lane. The yaw
373 angle curve (Fig. 6(c)) reflects all transition processes and characterizes the driving stability and
374 steerability of the model. The graphics in Fig. 6(a), 6(b), and 6(c) are smooth curves with
375 continuous changes in curvature. This implies a steady motion without any jerking of the vehicle,
376 confirming the quality of the model.

377 Fig. 6(d) illustrates the laws of changes in vehicle velocity during the overtaking process.
378 These speeds are determined by experimentally established average parameters via regression
379 equations with the addition of stochastic components. Fig. 6(e) shows a decrease in the distance
380 between approaching vehicles (from the initial 460.1 m). During the simulation, the movement
381 of the impeding, opposing, and passing vehicles is monitored.

382

383 6. Comparison of Field, Simulink, and Driving Simulator Results

384 The substantial variables characterizing the passing maneuver process include passing gap time,
385 following distance, and time to collision. Those variables were observed from the current field
386 study, Simulink model, and the driving simulator study based on Farah (2013). The comparison

Canadian Journal of Civil Engineering

between the results of the preceding studies is presented in Table 3. As noted, the values of the passing time gap are slightly different but substantially higher for the field data.

There was a slight difference in the gender distributions, where percentage of females in the field and driving simulator data was 32% and 31%, respectively. The age of the passing driver was slightly higher for the field data, with a mean of 34.4 years compared to a mean of 33 years for the driving simulator data. The speeds in the field study were substantially lower than those of the driving simulator study. Table 3 shows a substantial difference in the distributions of m , which was substantially lower in field data compared with driving simulator data.

The relative distance between the passing and opposing vehicles (df) was substantially higher with longer passing distances for the driving simulator data. The relative speed between passing and opposing vehicles ($V_p - V_o$), start time gap (G_s), end time gap (G_e), and time to collision (TTC) were substantially higher for the field data. The value of G_e was not presented in Farah (2013) but was calculated in this study. Fig. 7 shows a comparison of the estimated parameters of field, Simulink, and driving simulator data for start time gap, end time gap, and time to collision. Note that the field data and Simulink model results are relatively close since the realizations in the Simulink model are generated from the distributions established from the field data.

7. Conclusions

This paper has presented a modified gap acceptance model for passing maneuvers on two-lane highways using field data. Passing decisions were modeled regarding the decision to accept or reject an available passing gap. The model incorporates variables that capture the effect of driver

Canadian Journal of Civil Engineering

characteristics, and the attributes of the specific passing gap that are evaluated by the driver.

Based on this research, the following comments are offered:

1. For the passing time model, regression formulas were developed for initial time, starting gap, ending gap, and time to collision, which are necessary elements of passing maneuvers. The driver factors included gender, age, driving experience, and average weekly driving hours. The models included variables related to the gap itself such as the size of the available passing gap, the speed of the passing, impeding, and opposing vehicles, and the gap between the passing and impeding vehicles. For the gap acceptance model, the gap was formulated using a regression model in which the driver's age and driving experience were found to be statistically substantial.
2. The models were estimated using data collected in field studies conducted on two-lane highways. Advanced technologies involving in-vehicle video data recording and a GPS data logger were used in data collection. These methods provide improved video image quality and the possibility of determining complete trajectories with increased accuracy. These tools allowed the researchers to obtain data about passing maneuvers with greater efficiency and accuracy.
3. A SIMULINK model that implements the proposed gap acceptance framework was presented in this paper. The simulation results were validated for a design speed of 80 km/h and revealed comparable statistical values with those of previous studies.
4. The comparison of field and driving simulator data showed that the relative distance between passing and opposing vehicles of the driving simulator data was substantially higher. On the other hand, the relative speed between passing and opposing vehicles, start time gap, end time gap, and time to collision were substantially higher for the field data. The results of

Canadian Journal of Civil Engineering

Simulink model were relatively close to those of the field data, as expected. Field data are recommended for future studies since such data represent driver characteristics in a real life environment. With current advanced technologies, a large amount of data can now be collected in the field with high accuracy.

5. This study was based on field data collected on two-lane highways with a speed limit of 80 km/h. Future research may explore gap acceptance for speeds ranging from 70 to 90 km/h. In addition, the potential implementation of the presented gap acceptance model for in-vehicle collision warning systems should be explored. Implementation of the presented concept of gap acceptance in left driving systems, such as on Australian highways, should also be explored. It appears that the concept would be applicable as the decision-making process is similar. However, since driver behavior might be different, estimation of relevant parameters may be needed.

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LIST OF FIGURES

Figure 1. Elements of the passing maneuver

Figure 2. Frequency distributions of observed passing maneuver field data: (a) gap length

($\ln(GL)$); (b) Initial distance; (c) Speed differential (m); and (d) Passing vehicle speed (V_p)

Figure 3. Logic of the Simulink model

Figure 4. Simulink model of plane single unit vehicle (SUV) dynamics

Figure 5. State-flow chart of maneuver arrangement by steering control

Figure 6. Simulation output: (a) passing vehicle acceleration during overtaking, (b) passing vehicle lateral displacement, (c) passing vehicle yaw turning, (d) vehicle longitudinal velocity, (e) distance between passing and opposing vehicles

Figure 7. Comparison of the estimated parameters of field, Simulink, and driving simulator: (a) start time gap, (b) end time gap, (c) time to collision.

526

Figure 1 Elements of the passing maneuver

527
528

Draft

529

Figure 2 Frequency distributions of observed passing maneuver from field data: (a) Gap length (ln(GL)), (b) Initial distance, (c) Speed differential, and (d) Passing vehicle speed (V_p)

Canadian Journal of Civil Engineering

Figure 3 Logic of the Simulink model

Figure 4 Simulink model of plane single unit vehicle (SUV) dynamics

Figure 5 State-flow chart of maneuver arrangement by steering control

Canadian Journal of Civil Engineering

Figure 6 Simulation output: (a) Passing vehicle acceleration during overtaking, (b) Passing vehicle lateral displacement, (c) Passing vehicle yaw turning, (d) Vehicle longitudinal velocity, (e) Distance between passing and opposing vehicles

Figure 7 Comparison of the estimated parameters of field, Simulink, and driving simulator output: (a) Start time gap, (b) End time gap, (c) Time to collision

562

LIST OF TABLES

563 Table 1 Results of passing maneuver parameters of field study and their statistical characteristics

564 Table 2 Statistical results of estimated passing parameters

565 Table 3 Comparison of the estimated parameters of field studies, Simulink, and driving simulator

566

567

568

Draft

Table 1. Results of passing maneuver parameters of field study and their statistical characteristics^a

Variable ^b	Dist.	Mean	SD	DF	t-value	P-value	Chi-Sq	K-S	95th %	99th %
Vp (m/s)	Weibull	20.10	2.39	484	20.10	0.16	13.29	0.10	23.52	24.79
Vi (m/s)	Weibull	16.37	1.94	440	16.37	0.03	18.31	0.12	18.96	20.33
Vo (m/s)	Weibull	17.23	4.98	638	17.23	0.00	40.49	0.15	22.23	23.39
m (m/s)	Weibull	3.73	1.64	405	3.40	0.21	12.14	0.09	6.68	9.21
Acc(m/s ²)	Lognorm	0.61	0.30	49	0.61	0.09	15.57	0.12	1.21	1.52
Dec(m/s ²)	Lognorm	0.27	0.30	51	-0.27	0.00	26.77	0.12	0.09	0.23
t1 (s)	Lognorm	3.57	0.63	205	3.57	0.00	183.00	0.15	4.50	5.00
t2 (s)	Lognorm	9.60	2.45	457	4.99	0.21	11.69	0.09	14.58	15.75
Gs (s)	Lognorm	4.90	1.78	368	2.83	0.01	20.83	0.12	8.94	11.91
Ge (s)	Lognorm	3.16	1.00	278	2.06	0.18	12.14	0.05	5.38	5.86
TTC (s)	Weibull	6.11	4.66	581	-	0.00	19.68	0.67	15.69	17.54

^a DF: degree of freedom; Dist: Distribution; Chi-Sq: Chi-Square Statistic; K-S: Kolmogorov-Smirnov statistic; TTc alpha: 1.1674; TTc beta: 6.0788.

^b Vp = passing vehicle speed (m/s); ^b Vi = impeding vehicle speed (m/s); ^b m = speed difference (m/s); ^b Acc = passing vehicle acceleration (m/s²); ^f Dec = passing vehicle deceleration (m/s²); ^g t₁ = initial passing time (s); ^h t₂ = passing time (s); ^b Gs = starting gap (s); ^b Ge = ending gap (s); ^b TTC = time to collision (s).

Canadian Journal of Civil Engineering

Table 2. Statistical results for estimated passing parameters of linear regression model

Variables	Coefficient	Standard error	t-value	p-value
(a) Initial Passing Time (t ₁)				
Constant	3.810	0.353	10.79	<.0001
Gender	0.100	0.174	-0.58	0.57
Age (year)	0.021	0.018	1.14	0.26
Exp (year)	-0.025	0.021	-1.23	0.22
Awh (h)	-0.020	0.011	-1.88	0.06
m (m/s)	-0.036	0.043	-0.84	0.41
Model Root MSE	0.592			
Model F-Value	4.06			
(b) Start Time Gap Time (Gs)				
Constant	2.646	0.874	3.03	0.00
Gender	1.964	0.430	4.57	<.0001
Age (year)	0.213	0.045	4.72	<.0001
Exp (year)	-0.244	0.051	-4.81	<.0001
Awh (h)	-0.117	0.027	-4.40	<.0001
m (m/s)	-0.245	0.105	-2.33	0.02
Model Root MSE	1.463			
Model F-Value	10.86			
(c) End Time Gap (Ge)				
Constant	2.324	0.481	4.83	<.0001
Gender	1.003	0.229	4.38	<.0001
Age (year)	0.033	0.023	1.41	0.16
Exp (year)	-0.049	0.027	-1.87	0.06
Awh (h)	-0.054	0.014	-3.89	0.00
df (m)	0.003	0.001	4.72	<.0001
Model Root MSE	0.769			
Model F-Value	15.39			
(d) Time to Collision (TTC)				
Constant	15.751	2.941	5.36	<.0001
Gender	0.236	1.181	-0.20	0.84
Age (year)	-0.125	0.121	-1.03	0.30
Exp (year)	0.062	0.138	0.45	0.66
Awh (h)	0.109	0.071	1.53	0.13
Vo (m/s)	-0.482	0.082	-5.92	<.0001
Model Root MSE	3.984			
Model F-Value	8.7			

Table 3. Comparison of the estimated parameters of field, Simulink, and driving simulator data

Sample	Field Data		Simulink Data		Driver Simulator Data	
Variable	Mean	SD	Mean	SD	Mean	SD
GT (s)	8.06	2.33	6.82	1.57	7.10	2.20
GD (m)	161.01	45.81	167.0	44.15	175.50	56.30
Vp (km/h)	72.36	8.61	83.94	8.79	75.60	21.10
d12 (m)	52.49	17.09	36.91	5.49	13.50	10.30
Vi (km/h)	58.91	6.97	59.27	8.18	60.50	7.50
m (km/h)	13.44	5.89	12.76	4.63	15.10	13.90
D (m)	451.25	109.45	500.7	70.18	480.40	203.60
Vp – Vo (km/h)	10.32	10.82	12.50	11.03	0.30	8.20
Gs (s)	4.90	1.78	4.19	1.21	1.60	1.30
Ge (s)	3.16	1.00	2.63	0.517	5.50	7.00
TTC (s)	6.11	4.66	5.57	1.31	3.90	4.10

^a GD = gap distance corresponding to GT and D = Initial distance between passing and opposing vehicles, and Vp – Vo = relative speed.