Investigation of Influential Variables to Predict Passing Rate at Short Passing Zones on Two-Lane Rural Highways

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Abstract

The passing zone (PZ) is that part of two-lane highways in which drivers can safely overtake slower vehicles. Several studies have presented passing rate models in the PZ. However, there is no model to predict the passing rate in PZs shorter than 350 m. Furthermore, the effect of variables such as lane width, and the proportion of motorcycles on the passing rate were not investigated in previous works. This study assessed the effects of these variables on the passing rate and present a prediction passing model for short PZs. Data were collected from seven PZs using a drone on three different two-lane rural highway segments in Iran. The results showed that the passing rate depends on the lane width, absolute vertical grade, the flow rate in both directions, directional split, the proportion of heavy vehicles in the subject direction, and the proportion of motorcycles in the subject direction. Short PZ length values did not have a significant effect on the passing rate. The passing capacity occurred at a flow rate of 680 veh/h in both directions irrespective of the directional split.

Keywords: passing rate, short passing zone, two-lane rural highway, lane width, the proportion of motorcycles.

1. Introduction

On two-lane highways, faster vehicles are forced to follow slow vehicles until they reach a stretch of road which provides a passing opportunity, which depends on a gap in oncoming traffic and sight distance. The passing zone (PZ) provides a sight distance value which is sufficient for passing maneuvers. Where many passing maneuvers are possible, the traffic operation performance will improve. Passing demands and passing capacity (maximum passing rate) have a considerable impact on operation and driver perception of service. The passing rate indicates the number of passing maneuvers conducted in an hour by vehicles travelling in the same direction on a two-lane road.

The *Highway Capacity Manual* (HCM) (TRB, 2010) used the percent time spent following (PTSF) as a surrogate measure for passing demand to measure the operating performance of two-lane rural highways. However, HCM does not use the passing rate in the operation analysis because of the lack of comprehensive studies in this area. Passing rate modelling requires accurate observational field data: each individual vehicle needs to be constantly monitored while engaged in passing maneuvers. Hence, field data are difficult to collect due to the considerable length of PZs. For example, Mwesige, et al. (2016) used pneumatic tubes and camcorders mounted on tripods placed by the roadside along the PZ. Moreno, et al. (2013) used a mobile traffic laboratory which was equipped with six digital video cameras installed on an elevated platform.

Harwood, et al. (2008) presented two categories for the PZs: short PZs (PZ lengths shorter than 240 m) and long PZs (PZ lengths equal to 300 m or more). Using traffic simulation analysis, they showed that very few passing maneuvers occurred in short PZs. Their field observations also showed that only 0.4% of all vehicles made passing maneuvers in short PZs while 92% of passing maneuvers ended in no-passing zones (NPZ). Hence, their conclusion that short PZs contribute little to operational efficiency. However, they did not develop the passing rate prediction model for PZs. While a few field studies investigated the passing rate models (Mwesige, et al., 2016, Moreno, et al., 2013, Hegeman, 2008), none of them considered short PZs in their analysis. Furthermore, the effects of two explanatory variables - lane width and proportion of motorcycles on the passing rate - were not investigated in previous works.

To address this gap in knowledge, this study has investigated the effects of geometry and traffic-related variables, including the lane width and proportion of motorcycles, on the passing rate in PZs shorter than 350 m. Videos of vehicles involved in passing maneuvers were collected along short PZs using a drone. Video analyses were carried out to obtain independent variables that were then used to develop a first passing rate model for those maneuvers ending in the PZ (i.e., PZ-PZ and NPZ-PZ), and a second passing rate model for those which both start and end in the PZ (i.e., PZ-PZ). The two models are appropriate for countries where it is legally accepted that passing maneuvers may start in the NPZ and end in the PZ (NPZ-PZ), and to countries where they must start and end in the PZ (PZ-PZ) (Mwesige et al., 2016).

The manuscript is organized as follows: Section 2 presents a literature review on passing frequency along PZs; Section 3 explains how to model the passing rate statistically and also introduces the study sites and data collection method; Section 4 provides the results of the study, while the discussion of the results is presented in Section 5; Section 6 provides the main findings and addresses implications, recommendations, and future work needs.

2. Background

Wardrop (1952) offered a theoretical model to estimate passing demand from the speed distribution while assuming an ideal situation with no opposing traffic and no passing sight limitations. He used eq.(1) to calculate the number of passing maneuvers per kilometer per hour (P_n):

$$P_n = 5.6\left(\frac{V_S{}^2 \cdot \sigma_s}{\bar{\mu}_s^2}\right) \tag{1}$$

where V_S is traffic flow in the subject direction [veh/h], $\bar{\mu}_s$ is the average of space mean speeds [km/h] and σ_s is the standard deviation of space mean speed [km/h].

Daganzo (1975) developed a theoretical negative exponential passing rate model based on traffic flow in both directions to consider the reduction in passing opportunities due to oncoming traffic. He assumed that traffic flow and speed values were the same in both directions.

McLean (1989) proposed a formula for passing opportunities which used both oncoming traffic and sight distance limitations as follow:

$$P(o.t) = P(g > 30) \times P(road) \tag{2}$$

where *P(o.t)* is the probability of an overtaking opportunity, *P(g>30)* is the proportion of time in which there is a gap larger than the critical gap (30 s), and *P(road)* is the proportion of road length which is suitable for passing. In McLean's method, a passing maneuver is possible when the opposite gap is larger than 30 s (critical gap). He calculated *P(g>30)* as a function of the proportion of following vehicles and mean free headway. McLean (1989) determined *P(road)* as a function of percentage of PZs length along the road segment, frequency of NPZs, and speed of traffic flow.

Dommerholt and Botma (1988) attempted to capture both passing opportunities and passing demand for the development of a passing rate model. They developed the theoretical passing rate as a function of the standard deviation of the speed and the density of vehicles. To calculate the *expected number of overtaking maneuvers,* they reduced the theoretical passing rate using the probability that the passing maneuver was possible. To verify their proposed model, Dommerholt and Botma (1988) investigated six locations. Real passing rates were lower than the values obtained from the Dommerholt and Botma equation. To reduce the theoretical passing rate, they took the following two factors into account: (1) that the passing maneuver does not occur if the speed difference between the lead and following vehicles is below a threshold value, and (2) that the passing rate reduces linearly with increasing mean platoon length for traffic flows above 400 veh/h.

More recently, Tuovinen and Enberg (2006) developed separate linear regression models for individual road segments in order to estimate passing rates. One-way traffic flows were used as the only predictor variables in the quadratic form. Hegeman (2008) studied passing maneuvers along two road segments, one of which had a passing prohibition. This prohibition was applied according to the Dutch Sustainable Safety Program (Wegman and Aarts, 2006), which suggested the prohibition of passing maneuvers as a means to improve safety. Hegeman (2008) developed a multivariate linear regression model to estimate passing rates based on subject and oncoming flow rates:

$$OF = 1.6\times10^{-11}\times V_S^{1.5}(1700 - V_O)^{2.5} \tag{3}$$

where OF is the passing rate per kilometer per hour, V_S is traffic flow in the analysis direction [veh/h], V_O is traffic flow in the opposite direction [veh/h].

Moreno, et al. (2013) developed a Poisson regression model such as that in Equation (4) to predict the passing frequency in the subject direction for a 15-min period (PF):

$$PF = \exp\begin{pmatrix} -4.57904 - 0.00125\cdot V^2 - 0.0000013\cdot L_{PZ}^2 \\ +2.75645\cdot D_S + 0.04093\cdot V + 0.003455\cdot L_{PZ} \end{pmatrix} \tag{4}$$

where V is the two-way traffic volume for a 15-min period [veh/h], L_{PZ} is the length of PZ [m], and D_S is the directional split in the subject direction. They used two different road segments with different lengths of PZ in two directions and used 114 periods of 15 min per passing zone to develop their model. The maximum passing rate occurred at a two-way traffic volume between 600 and 700 veh/h for all PZs.

Mwesige, et al. (2016) proposed a model to predict the passing rate per hour (*P*) in the subject direction at PZs based on traffic and geometric parameters as follows:

$$P = \exp\begin{pmatrix} -5.089 + 1.123 \cdot L_{PZ} - 0.1948 \cdot L_{PZ}^2 + 0.09951 \cdot V_G \\ +0.01917 \cdot V - 0.00002401 \cdot V^2 + 0.008177 \cdot S_{85} \\ +0.0376 \cdot D_S + 0.05555 \cdot P_{HV} + 0.0008065 \cdot P_{HV}^2 \end{pmatrix} \quad (5)$$

where L_{PZ} is the length of PZ [km], V_G is the absolute vertical grade [%], V is the total traffic volume in the two travel directions [veh/h], S_{85} is the 85th percentile speed [km/h], D_S is the directional split in the subject direction, and finally P_{HV} is the proportion of heavy vehicles.

Mwesige, et al. (2016) used a total of 96 observations to estimate their models. They found that by increasing the percentage of heavy vehicles, the passing rate rose, then reached a peak of 35% before falling back. Based on their model, passing capacity occurred at the two-way volume of 400 veh/h. Other variables including the length of PZ, absolute vertical grade, and directional split in the subject direction were significant at the 95% confidence level. The 85th percentile speed was significant at the 90% confidence level. Table 1 presents a list of the above-mentioned studies and their corresponding contributions (e.g., explanatory variables) and shortcomings.

A number of field studies were conducted to find the influential variables on the passing rate in PZs. No study presented a passing rate prediction model for short PZs. Furthermore, the effects of both the proportion of motorcycles and lane width variables have yet to be investigated.

3. Objectives, methodology, and data collection

3.1 Objectives

This research aims to determine the effects of geometric (i.e., short PZ length, lane width) and traffic-related variables (i.e., the proportion of motorcycles) on the passing rate and the passing capacity. This research used field data collected with a drone to develop models for predicting the passing rate in the PZs. In particular, two models were developed: (i) Model 1 estimates the number of passing maneuvers in 15 minutes ending in PZ (PZ-PZ and NPZ-PZ) in the subject direction, while (ii) Model 2 estimates the number of passing maneuvers in 15 minutes which both start and end in the PZ in the subject direction (PZ-PZ).

3.1. Variables

3.1.1 Dependent variable

In most cases, passing maneuvers that start and end in the PZ (PZ-PZ maneuvers) have sufficient sight distance (Khoury and Hobeika, 2007). Passing maneuvers that begin in the NPZ and end in the PZ (NPZ-PZ maneuvers) are more likely to be initiated near the beginning of the PZ (Mwesige, et al., 2016). Harwood, et al. (2008) categorized them as *jumping*. Although drivers do not have a passing sight distance sufficient to complete the entire passing maneuver, it should be enough to reach the abreast position, at which point they can abort the maneuver if necessary. Hence, drivers have a sight distance which is sufficient for the risk evaluation of passing maneuvers ending in the PZ (PZ-PZ and NPZ-PZ). However, many countries legally accept only those maneuvers that start and end in the PZ (PZ-PZ), while others accept both cases (Mwesige, et al., 2016).

In light of the above, two dependent variables were considered: (i) the number of passing maneuvers ending in the PZ in the subject direction, and (ii) the number of passing maneuvers starting and ending in the PZ in the subject direction.

3.1.2 Explanatory variables

Explanatory variables were derived from both theoretical and field observation models described in the Background section; however, some additional variables expected to be influential were also examined.

Variables were categorized into two groups: (i) geometry-related variables like PZ length, upstream NPZ length, absolute vertical grade, and lane width, and (ii) traffic-related variables like traffic flow rate in both directions, traffic flow rate in the subject direction, traffic flow rate in the opposite direction, directional split of traffic volume, proportion of heavy vehicles, proportion of motorcycles, mean free-flow speed, standard deviation of free-flow speed, and 85^{th} percentile of free-flow speed.

3.2. Statistical analysis

The number of passing maneuvers takes only non-negative integer values. Thus, in this case, the count data models provide an appropriate framework for estimating the number of passing maneuvers. Poisson regression is the most popular method for modeling count data. In the Poisson regression model, the probability of observation *i*-th having y_i completed passing maneuvers in 15-min, is given by:

$$P(y_i) = \frac{\exp(-\lambda_i)\lambda_i^{y_i}}{y_i!} \quad (6)$$

where λ_i is the Poisson parameter, which is equal to the number of expected passing maneuvers for a *i*-th 15-min. One of the properties of a Poisson distribution is that the mean of the counting process equals its variance. The Poisson regression model is estimated by specifying λ_i as a function of explanatory variables, as shown in:

$$\lambda_i = E\left[y_i\right] = VAR\left[y_i\right] = \exp\left(\beta X_i\right) \tag{7}$$

where X_i is the vector of explanatory variables, and β is the vector of estimable parameters from observed data. This model was estimated using the standard maximum likelihood method. The likelihood function computed for all observations is:

$$L\left(\beta\right) = \prod_i \frac{\exp\left[-\exp\left(\beta X_i\right)\right]\left[\exp\left(\beta X_i\right)\right]^{y_i}}{y_i!} \tag{8}$$

The equality between mean and variance represents a limitation in the case of over-dispersed data (i.e., when the variance is greater than the mean). In many studies, the omitted variables are the main reason for overdispersion (Washington, et al., 2010). Overdispersion leads to inflation in estimated standard errors of estimated parameters, but it does not affect the magnitude of estimated parameters (Cameron and Trivedi, 2013). The Negative Binomial model is able to account for overdispersion, which is derived by rewriting Equation (7) into Equation (9) :

$$\lambda_i = \exp\left(\beta X_i + \varepsilon_i\right) \tag{9}$$

where $\exp(\varepsilon_i)$ is the disturbance term, which has a Gamma distribution with mean one and variance α. This term makes it possible to have a variance different from the mean, as shown in:

$$VAR\left[y_i\right] = E\left[y_i\right] + \alpha E\left[y_i\right]^2 = \lambda_i + \alpha \lambda_i^2 \tag{10}$$

where α is the overdispersion parameter. When α is zero, the negative binomial and Poisson models are the same, therefore the choice between these two models depends on the value of α. The Negative Binomial probability distribution is:

$$P(y_i) = \frac{\Gamma\left((1/\alpha) + y_i\right)}{\Gamma(1/\alpha)\, y_i!} \left(\frac{1/\alpha}{(1/\alpha) + \lambda_i} \right)^{1/\alpha} \left(\frac{\lambda_i}{(1/\alpha) + \lambda_i} \right)^{y_i} \tag{11}$$

where $\Gamma(.)$ is the Gamma function. The parameters of the negative binomial model were able to be estimated using again the maximum likelihood method (Cameron and Trivedi, 2013).

In this study, the passing rate data were obtained from seven PZs along three different two-lane rural highways. Therefore, there may be a correlation among observations in each PZ because the data from each PZ may share unobserved effects. Random effects models should be considered to account for correlations of observation in each PZ. Random effects may be considered in count data models based on:

$$Ln\left(\lambda_{ij}\right) = \beta X_{ij} + \eta_j \tag{12}$$

where λ_{ij} is the expected number of completed passing maneuvers for the *i*-th 15-min belonging to *j*-th PZ, X_{ij} is a vector of explanatory variables, β is a vector of corresponding parameters, and η_j is a random effect for observations of the *j*-th PZ. Based on this specification, the random-effects Poisson model is:

$$P\left(y_{ij} \middle| X_{ij}, \eta_j\right) = \frac{\exp\left[-\exp\left(\beta X_{ij}\right)\exp\left(\eta_j\right)\right]\left[\exp\left(\beta X_{ij}\right)\right]}{y_{ij}!} \tag{13}$$

It is assumed that η_j is randomly distributed across groups (PZs) such that $\exp(\eta_j)$ has Gamma distribution with mean one and variance φ. For the random-effect Poisson model, the mean value is not equal to the variance, and the variance to mean ratio is $1+ \lambda_{ij}/(1/ \varphi)$. If φ is zero, the random-effects and pooled (Poisson) models are not significantly different. The random-effects

Negative Binomial model can be derived using the same approach as above for the random-effects Poisson model, which was described by Haussman, et al. (1984).

In this paper, the presence of overdispersion and correlation among observations was examined, then the appropriate model was chosen to estimate the passing rate.

3.3. Study sites and data collection

Data were collected from seven PZs on three different two-lane rural highways in Iran (Jiroft-Faryab, Jiroft-Baft, and Jiroft-Kerman highways). All passing zones were along straight sections and almost constant vertical grades. Table 2 presents the geometric characteristics and posted speed limits for PZs. PZ length varied from 164 to 345 meters. Lane width was between 3 and 3.75 m, and the absolute vertical grade was between 0.5 to 9.5%. PZ n.7 (Table 1) is the only one with a shoulder, which is paved. Figure 1 shows diagrams of the horizontal and vertical alignment around the investigated sections.

Data were collected using a Phantom 4 Pro drone (Figure 2) equipped with a 1-inch 20-megapixel sensor capable of shooting 4K/60fps video and a 3-axis gimbal to stabilize the camera oscillation. During video recording, the minimum altitude of the drone was 150 m to avoid any impact on driver behavior. Data were collected during 38 flights lasting 15-20 minutes each. The weather conditions during data collecting were clear and good.

Using road markings at the beginning of the PZs (their lengths were measured in the field) and the timestamps of vehicles determined by using the open-source video analysis software Kinovea (Charmant, 2016), vehicle speeds and time headways were calculated. The vehicle type was visually recorded. Free-flow speeds were determined for passenger cars that were found to operate in free-flow conditions based on at least 6 s headway (Al-Kaisy and Karjala, 2008).

Geometry variables such as lane width, vertical grade, and PZ length were measured in the field. The hourly flow rate was calculated as the volume of vehicles in 15 minutes multiplied by four.

4. Results

Table 3 presents a summary of the observed variables at the PZs. The average number of passing maneuvers ending in the PZ in the subject direction (N_{PZ}) was 5.0 passes per 15 minutes, reaching a maximum value of 33 passes per 15 minutes. The average and maximum values of the number of passing maneuvers starting and ending in PZ in the subject direction (N_{PPZ}) were 2.3 and 21, respectively. The average of N_{PZ} was more than two times that of N_{PPZ}, which means that more than half of the drivers ending their maneuver in PZ, started it from NPZ. The flow rate in both directions had a range between 212 and 840 veh/h, with a directional split up to 80%, which provides a suitable combination for analysis. The directional split equals 30% means ($V_S = 0.3V$, and $V_O = 0.7V$). The proportion of motorcycles in the subject direction had a maximum value of 14%, which was a considerable one for rural highways. Mean free-flow speed for every 15 minutes had an average of 85.3 km/h with an average standard deviation of 16.0 km/h. Based on the explanatory variables presented in Table 3, the N_{PZ} and N_{PPZ} are estimated using count data models.

Table 4 presents a summary of the estimation of Models 1 (to estimate the N_{PZ}) and 2 (to estimate the N_{PPZ}). To find a suitable model for estimating the passing rate, overdispersion in the data and correlations among observations in each PZs were analyzed. Table 4 shows the results of the likelihood ratio test for the overdispersion parameter (α): it illustrates that α is statistically highly insignificant for both Model 1 (p-value = 0.500) and Model 2 (p-value = 0.379). This means that α is equal to zero, i.e., there is no difference between the Negative Binomial and Poisson models. Table 4 also shows that the random-effects parameter (φ) is highly insignificant for both Model 1 (p-value = 1.00) and Model 2 (p-value = 1.00). These results imply that the parameter of φ is statistically equal to zero, and there is no difference between the random-effects and pooled (Poisson) models. Hence, the Poisson model was chosen to estimate the passing rate in this study. The passing rate models were estimated using the *STATA* statistical software (StataCorp, 2017). Different model forms using variables that were listed in Table 3 were estimated. In the following, the results of model estimation for Models 1 and 2 are carefully described.

4.1. Estimating N_{PZ} (Model 1)

The overall significance of Model 1 was evaluated using the likelihood ratio test, which was significant at the 95% confidence level (χ^2 = 226.73, p-value < 0.0001). Deviance and Pearson tests were conducted to assess the goodness-of-fit of the model. The insignificant test statistics (p-value > 0.05) indicate that the model fits the data well. As additional descriptive measures of goodness-of-fit, Cragg-Uhler R^2 (Cragg and Uhler, 1970) and McFadden's R^2 (McFadden, 1973) were calculated (values equal to 0.950 and 0.418 respectively). These two statistics confirm that the model fits the data well. Wald tests were carried out to identify significant variables which were retained in the model.

Variables of the PZ length, upstream NPZ length, 85th Percentile free-flow speed, and standard deviation of free-flow speed were statistically not significant at the confidence level of 90% and, therefore, removed from the model. However, the signs of the coefficients for these variables were consistent with a priori expectation. The lane width was found to be highly significant (*p*-value < 0.001). Its positive sign implies that an increase in lane width leads to an increase in the passing rate. Table 5 shows that the average marginal effect of lane width on passing rate at 15 min is equal to 7.47, which means that if the lane width increases by 0.2 m, N_{PZ} increases by 6 passes per hour on average. The marginal effect of lane width increases by increasing its value. The absolute vertical grade was statistically significant at the 95% confidence level (*p*-value < 0.01). Based on its marginal effect reported in Table 5, each 1% increase in the absolute vertical grade, the N_{PZ} increases by the hourly passing rate of 1.56 passes on average.

The flow rate in both directions (V) and its quadratic term had a significant effect at the 95% confidence level (*p*-values < 0.05). This variable has different effects based on its value. Figure 3 illustrates the average marginal effects of flow rate in both directions on N_{PZ} for different values of the flow rate. This figure shows that the positive marginal effect peaked at the flow rate of 400 veh/h. The figure shows a sharp fall in the marginal effect of flow rate such that it was zero at the flow rate of 680 veh/h. From this value, the effect of flow rate on N_{PZ} was negative, which means that at an increased flow rate (greater than 680 veh/h), the passing rate decreased. The directional split of traffic volume (D_S) was also a significant variable at the level of 0.001. With an increase in D_S, the traffic in the subject direction increases and the traffic in the opposite direction decreases, with the former resulting in an increase in the passing demand, and the latter leading to an increase in passing opportunities. Another way to capture this effect in the models is to use the two variables of the flow rate in the subject and flow rate in the opposite direction.

However, using flow rate and directional split variables presented better model results. The results show that with a 10% increase in directional split for subject direction, the N_{PZ} increased by 6.8 passes per hour on average.

The proportions of heavy vehicles (P_{HVS}) and motorcycles (P_{MCS}) to traffic volume in the subject direction were significant at the 95% and 90% confidence levels, respectively. The marginal effect of the P_{MCS} is almost twice that of the P_{HVS}. A five percent increase in P_{HVS} increased the N_{PZ} by 2 passes per hour on average. A five percent increase in P_{MCS} increases the passing rate by 4.2 passes per hour.

4.2. Estimating N_{PPZ} (Model 2)

Model 2 was significant at the 95% confidence level (χ^2 = 84.488, p-value < 0.0001). The results of the Pearson goodness-of-fit test suggest the model performed well (χ^2 = 226.73, p-value = 0.099). However, the Deviance statistic was significant (χ^2 = 90.559, p-value = 0.042).

The length of the PZ had a statistically significant effect on N_{PPZ} at the 95% confidence level (p-value < 0.01). Table 6 indicates that the average marginal effects of the PZ length on N_{PPZ} were 0.018, which means if the L_{PZ} increased 100 m, the N_{PPZ} increased by 7.2 passes per hour. The variables L_W, V_G, and D_S were also statistically significant as they were for Model 1. Their average marginal effects are presented in Table 6. Unlike Model 1, the two variables of P_{HVS} and P_{MCS} were statistically insignificant at the 95% confidence level.

5. Discussion

The upstream NPZ length did not have a significant effect on the passing rate. Mwesige, et al. (2016) reached a similar result on the effectiveness of the upstream NPZ length. They presented four factors that could explain this result. The two variables of 85th percentile free-flow speed and standard deviation of free-flow speed, like the study of Mwesige, et al. (2016), were statistically not significant at the 95% confidence level.

According to previous works, PZ length is statistically significant (Mwesige, et al., 2016, Moreno, et al., 2013). However, in this study, the PZ length had a strongly insignificant effect on passing maneuvers ending in the PZ (N_{PZ}). The PZs that previous works studied were within the range of 290-2990 m (Mwesige, et al., 2016) and 256-1270 m (Moreno, et al., 2013), respectively. The PZs in this study ranged from 164 to 345 m, with most of them on the short side. The suspect is that almost all drivers were familiar with the highways; hence they were aware of the short length of the PZs and anticipated their maneuvers to complete them safely. The results presented in Table 3 show that the average number of NPZ-PZ maneuvers was higher than that for the PZ-PZ ones. However, if only the N_{PPZ} were considered, the PZ length was significant. It may be concluded that drivers (most of whom were familiar with the road) adjust the starting point of their passing maneuver so as to complete it safely before the NPZ.

A sensitivity analysis of Model 1 explanatory variables was conducted to see how an explanatory variable affected the passing rate. To present the 15-min passing frequency as an hourly passing rate, N_{PZ} and N_{PPZ} are multiplied by four as equation (14) and (15) illustrate:

$$P_{PZ} = 4 \cdot N_{PZ} = 4 \cdot \exp\begin{pmatrix} -8.4586 + 1.4989 \cdot L_W + 0.0779 \cdot V_G + 0.00852 \cdot V - 6.28 \times 10^{-6} \cdot V^2 \\ +0.03381 \cdot D_S + 0.02044 \cdot P_{HVS} + 0.04307 \cdot P_{MCS} \end{pmatrix} \quad (14)$$

$$P_{PPZ} = 4 \cdot N_{PPZ} = 4 \cdot \exp\begin{pmatrix} -12.31318 + 0.00786 \cdot L_{PZ} + 1.71082 \cdot L_W + 0.06994 \cdot V_G \\ +0.01218 \cdot V - 10.2 \times 10^{-6} \cdot V^2 + 0.02636 \cdot D_S \end{pmatrix} \quad (15)$$

Figure 4 produces for $V_G = 3.5\%$, $P_{HVS} = 8.56\%$, $D_S = 50$, $L_W = 3.45$, and $P_{MCS} = 0\%$ in equation (14), except the variables that change in each figure.

Figure 4a provides information on the change in the passing rate of maneuvers ending in the PZ (P_{PZ}) for different values of the lane width at four different levels of the traffic flow rate (200, 400, 600, and 800 veh/h). The results show that by increasing the lane width, the passing rate increased. The marginal effect of lane width increased as the base value increased. For example, adding 0.1 m to a lane with 3.6 m width (base value) has more effect on the passing rate than adding 0.1 m to a lane with 3 m width. A wider lane width results in drivers taking more risks because it provides more room for passing and helps to prevent opposing vehicles from colliding. Furthermore, the marginal effect of lane width with respect to the flow rate is maximized at the traffic flow rate equal to 680 veh/h. Lane width had a highly significant effect in both Model 1 and Model 2. This variable was not evaluated in previous works because their PZs had the same lane width.

Figure 4b shows the effect(s) of absolute vertical grade on P_{PZ} at traffic flow rate levels of 200, 400, 600, and 800 veh/h. Unlike previous studies (Mwesige, et al., 2016, Moreno, et al., 2013, Hegeman, 2008) where sites were located on flat terrain, in this study the absolute vertical grade had a wide range from 0.58 to 9.5%. The results show that absolute vertical grade had a positive impact on the passing rate, and the impact had a peak respect to the traffic flow rate. The vertical grade reduces the speed of heavy vehicles, which causes the platoons. To consider this impact, HCM used an adjusted factor to calculate the demand flow rate (TRB, 2010).

Figure 4c shows the rise in the passing rate in the subject direction (P_{PZ}) caused by an increase in the proportion of heavy vehicles in the subject direction (P_{HVS}). Mwesige, et al. (2016) used the proportion of heavy vehicles in both directions (P_{HV}); however, this variable did not have a significant effect on the P_{PZ}. As the percentage of heavy vehicles in the subject direction increases, the number of platoons and their length grow, which increases the frustration and desire of drivers behind to pass (Penmetsa, et al., 2015, Polus and Cohen, 2009). Hence, P_{HVS} better explains the effect of the proportion of heavy vehicles on the passing rate in the subject direction than the P_{HV}. By increasing the P_{HVS}, the platooning and PTSF will increase, which leads to an increase in the demand for passing maneuvers. Drivers caught in a platoon behind slow vehicles (heavy vehicles for example) will attempt to conduct more passing maneuvers. The ability to pass is provided by the PZs if and when drivers find a gap in the opposite direction. Mwesige, et al. (2016) showed that the passing rate increases with the P_{HV} to a peak at 35% and then decreases. In this study, the highest levels of P_{HV} and P_{HVS} are 30.2 and 37.9%, respectively, and the results show an increase in the passing rate with an increase in P_{HVS} consistently with Mwesige, et al. (2016). The P_{HVS} did not have a significant effect on the number of passing maneuvers that start and end in the NPZ (P_{PPZ}). It is for this reason that, as observed in the recorded videos, the platoon discharges before the PZs, hence, most of the vehicles in the platoon start passing maneuvers in the NPZ.

Figure 4d illustrates the effect of the proportion of motorcycles in the subject direction (P_{MCS}) on the P_{PZ}. The figure indicates that the P_{PZ} increased as the proportion of motorcycles in the subject direction increased. The reason for the increase in the passing rate is that the vehicles needed shorter gaps to pass. Furthermore, motorcycles had lower speed (51 km/h on average) and width and drove close to the road edge (for roads without shoulders) or to the shoulders, which made it easier for drivers to pass them.

It should be noted that high-speed motorcycles are forbidden in Iran. Hence, this variable might prove to be insignificant in other countries. In fact, in the study conducted by Hegeman (2008), motorcycles accounted for less than 2% of traffic flow, and they did not consider this variable in their model. Similarly, other previous studies did not evaluate the effect of the proportion of motorcycles on the passing rate. Figure 5 illustrates the graphs of the passing rate in the subject direction and the traffic flow rate in both directions. Figures 4 was produced for V_G = 3.5%, P_{HVS} = 30%, L_W = 3.5 m, L_{PZ} = 300 m and P_{MCS} = 0%. These values were selected so as to be consistent with studies conducted by Mwesige, et al. (2016) and Moreno, et al. (2013) and make it possible for comparing. The graphs of P_{PZ} were plotted at five directional split levels of 20, 50, 60, 70, and 80%.

The results show that the directional split has a significant effect on the passing rate as shown by the fact that an increase in the directional split in the subject direction results in a similar increase in the passing rate. The directional split also had a significant effect on the studies of Mwesige, et al. (2016) and Moreno, et al. (2013). Hegeman (2008) employed both subject and opposite traffic volumes in her model instead of using two-way traffic volume and directional splits. The graphs of previous studies (Mwesige, et al., 2016, Moreno, et al., 2013, Hegeman, 2008) and P_{PPZ} in Figure 5 were plotted for a directional split of 50%. The model of Mwesige, et al. (2016) (Equation (5)) is very close to the model that predicts the P_{PZ} (Equation 14). Both models predicted the passing rate of passing maneuvers that ended in the PZs and also employed most of the explanatory variables for estimation compared to other previous studies, and it could be the reason for the more accurate prediction of these two models. Another reason could be the similarity in the traffic culture of the countries.

The models proposed by Hegeman (2008) and Moreno, et al. (2013) (Equation (3) and (4) underestimated the passing rate. Their studies were carried out in developed countries, which might explain the significant differences between passing rate values in their work and that of Mwesige, et al. (2016). Another reason for the lower prediction by Hegeman (2008) is due to the *Dutch Sustainable Safety Program*, which recommended that authorities design two-lane highways along which passing is prohibited, even where there is sufficient sight distance. In the study of Moreno, et al. (2013), the two studied PZs were too close to each other (less than 350 m), hence a reduction in the passing rate was possible.

Figure 5 shows that the passing rate of maneuvers ending in the PZ (P_{PZ}) is nearly two times that of the passing rate of maneuvers that started and ended in the PZ (P_{PPZ}). Furthermore, the PZ length had an insignificant effect on P_{PZ}. All of which implies that increasing the length of the short PZs does not lead to a significant increase in the passing rate and, by extension, more fluid traffic operations.

However, the high passing rates observed demonstrate that short PZs irrespective of their length have a significant effect on the operation of highways in Iran. Harwood, et al. (2008) observed that only 0.4% of all vehicles passed in the short PZs, while this value was 5% on average in Iran. Moreno, et al. (2016) studied the effects of PZ length (250-5000m) on the operational performance of two-lane highways. Their findings showed that average PZ length had an effect on traffic performance, while short PZs (250m) did not.

As shown in Figure 5, the passing rate for maneuvers ended in the PZ (P_{PZ}) peaked at the flow rate of 680 veh/h, after this a reduction was observed. This maximum value represents the passing capacity, which indicates the maximum effectiveness of PZs respect to flow rate in both directions.

Figure 5 shows the passing capacity for maneuvers that start and end in the PZ (P_{PPZ}) at the flow rate of 597 veh/h. Moreno, et al. (2013) found that the peak passing rate occurred at 600-700 veh/h, which is similar to the findings of this research. However, in the study conducted by Mwesige, et al. (2016), the passing rate reached its capacity at the flow rate in both directions at 400 veh/h. The maximum flow rate that they observed in their study was 426 veh/h. Hence, they could not estimate the effect of superior levels of flow rate on the passing rate. They stated that it was not possible to observe the passing capacity at 600 veh/h because the average headways were too short (Mwesige, et al., 2016). However, it should be noted that by increasing the flow rate, the platoons will increase and, commonly, several drivers in the platoons use a single gap in the opposite direction to pass the slow vehicle together.

6. Conclusion

This study evaluated the effects of geometric characteristics and traffic-related explanatory variables on the passing rate of short passing zones (PZs). The effectiveness of variables was obtained by generating Poisson regression models from aerial data collected from seven PZs.

The main conclusions of the study were as follows:

- the length of the short PZs did not have a significant effect on the passing rate of maneuvers ending in the PZ; hence, limited increases in length of the short PZs would not help to improve traffic operations since, in practice, a significant proportion of drivers start their passing maneuvers before reaching short PZs. Nevertheless, the results showed that short PZs had an important role in improving traffic operations in Iran irrespective of their length;
- the lane width had a highly significant effect on the passing rate;
- by increasing the proportion of motorcycles in the subject direction, the passing rate in the subject direction witnessed a significant increase;
- the proportion of heavy vehicles in the subject direction was a significant variable when estimating the passing rate in the subject direction, while the proportion of heavy vehicles in both directions proved insignificant;

- the passing capacity of the PZs occurred at the flow rate of 680 veh/h, and the maximum increase rate in the passing rate occurred at the flow rate of 400 veh/h.

The models presented support planners and designers in developing safety and operational analyses. Traffic flow rate is an important variable in planning for a highway. Based on the projected figures for passing capacity and predicted flow rate, planners could select between two-lane highways and other types of infrastructure. Limited increments in length would not lead to an improvement in traffic operations at short PZs. Other geometrics characteristics, e.g., the lane width, could play a more significant role. However, the increment in length of short PZs could significantly improve safety (Moreno, et al. (2015). Accordingly, future research should investigate the effect of short PZs on safety. From a safety perspective, increasing the flow rate beyond the passing capacity serves only to decrease the passing rate and increase driver frustration levels, which in turn could result in dangerous passing maneuvers. Furthermore, since in Iran, motorcycles travel at a slower speed than passenger cars, the estimated models suggest that an increase in the proportion of motorcycles increases the passing rate. Hence, safety experts should base their evaluation of safety performance on traffic volumes, passing capacity, and the proportion of motorcycles.

Heavy vehicles travel at a slower speed than passenger cars, and their speed decreases further as the absolute vertical grade increases. The result of this work showed that an increment in the proportion of heavy vehicles and/or the absolute vertical grade increases the passing rate. However, the passing maneuver is a demanding and dangerous task, so planners and designers should consider the safety implications of the proportion of heavy vehicles and vertical grades when deciding between two-lane highways and other facility types. To achieve more homogenous speeds, lower vertical grades have to be assumed at the design stage if a high percentage of heavy vehicles is expected.

Some variables such as shoulder width, pavement surface quality, and weather conditions need to be evaluated in future studies. Llorca, et al. (2013) concluded that the passing driver's behavior was different at night. Hence, an investigation into the passing rate at nighttime is needed. The posted speed limit could also affect the passing rate. In this study, there was not enough variation in this variable for analysis. Moreover, the strategies to enforce the speed limit could be important, and this aspect also requires field study in PZs. A simulation study conducted by Ghods and Saccomanno (2016) showed that differential speed strategies had a significant effect on the passing rate of passenger cars when overtaking heavy vehicles.

This study focused on short PZs, with length values between 164 and 345 m (Table 1). A wider range of PZ lengths could help to find cases where the length of PZ has a significant effect on the passing rate. To generalize the proposed models across different countries, future studies need to be carried out.

Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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Notation list

D_S = directional split of traffic volume

L_{PZ} = passing zone length

L_W = lane width

N_{PPZ} = number of passing maneuvers per 15 minutes starting and ending in PZ in subject direction

NPZ = no-passing zone

N_{PZ} = number of passing maneuvers per 15 minutes ending in the passing zone (PZ) in the subject direction

P_{HV} = proportion of heavy vehicles in both directions

P_{HVS} = proportion of heavy vehicles in the subject direction

P_{MCS} = proportion of motorcycles in the subject direction

P_{PPZ} = number of passing maneuvers per hour starting and ending in PZ in subject direction

P_{PZ} = number of passing maneuvers per hour ending in the passing zone (PZ) in the subject direction

PTSF = percent time spent following

PZ = passing zone

V = flow rate in both directions

V_G = absolute vertical grade

V_O = flow rate in the opposite direction

V_S = flow rate in the subject direction

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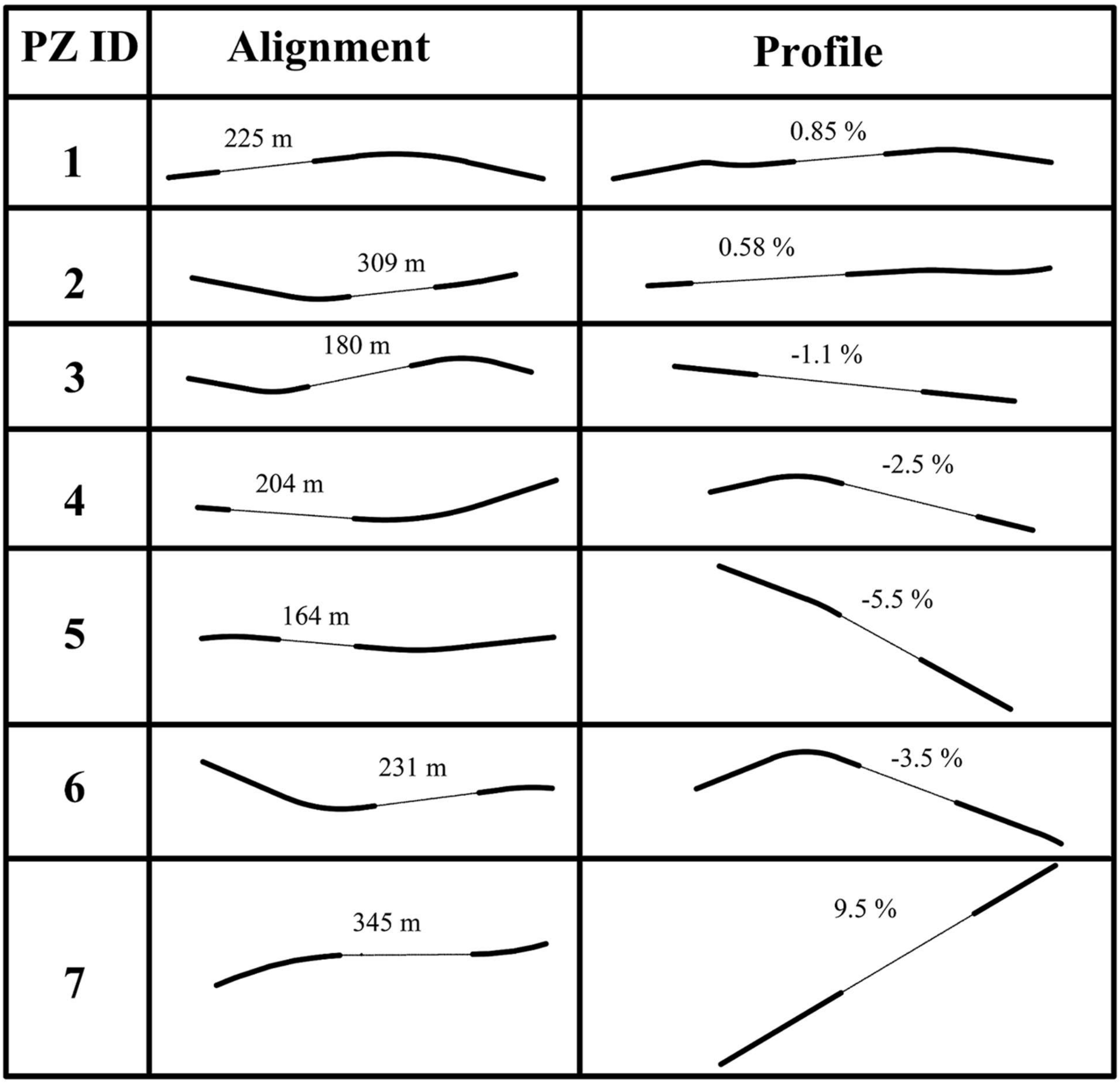

Figure 1: Diagrams of the horizontal and vertical alignment around the PZs

Figure 2: Phantom 4 Pro drone

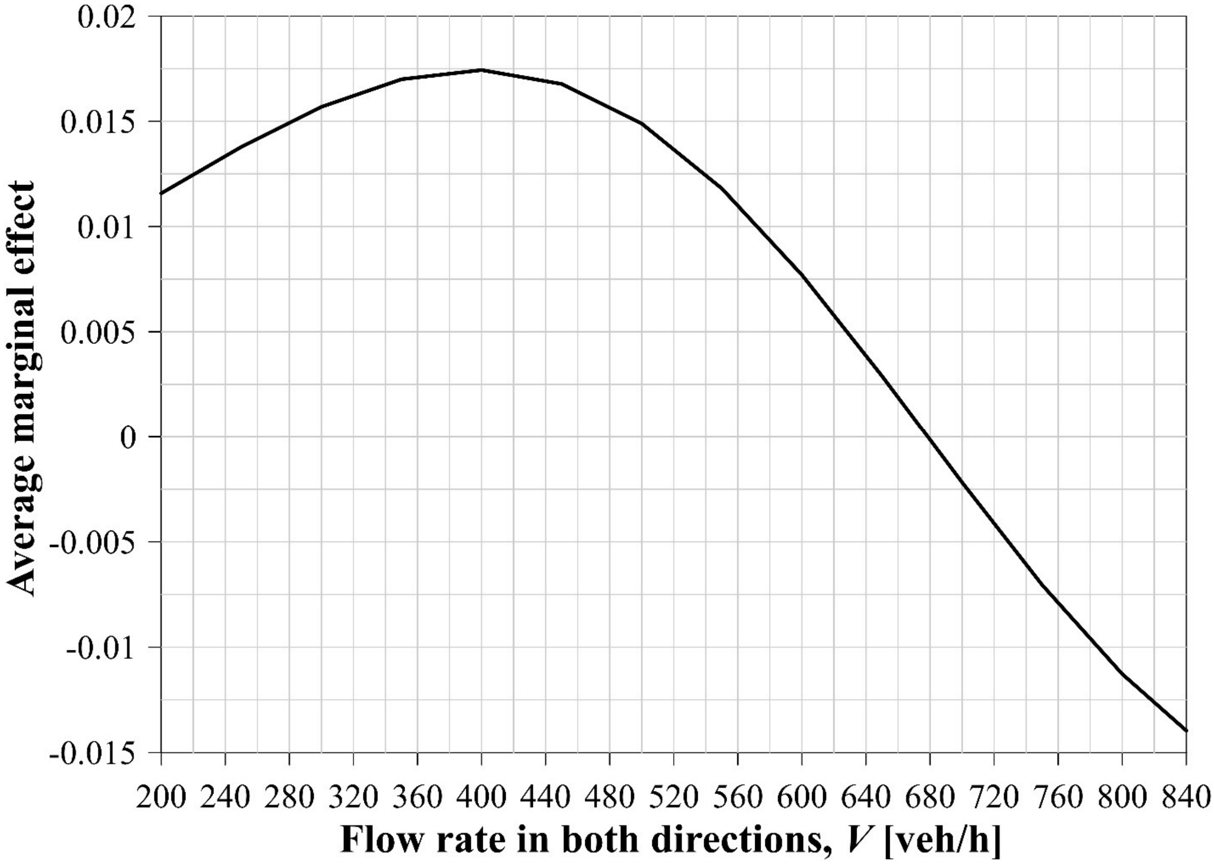

Figure 3: The average marginal effects of the flow rate in both directions on NPZ

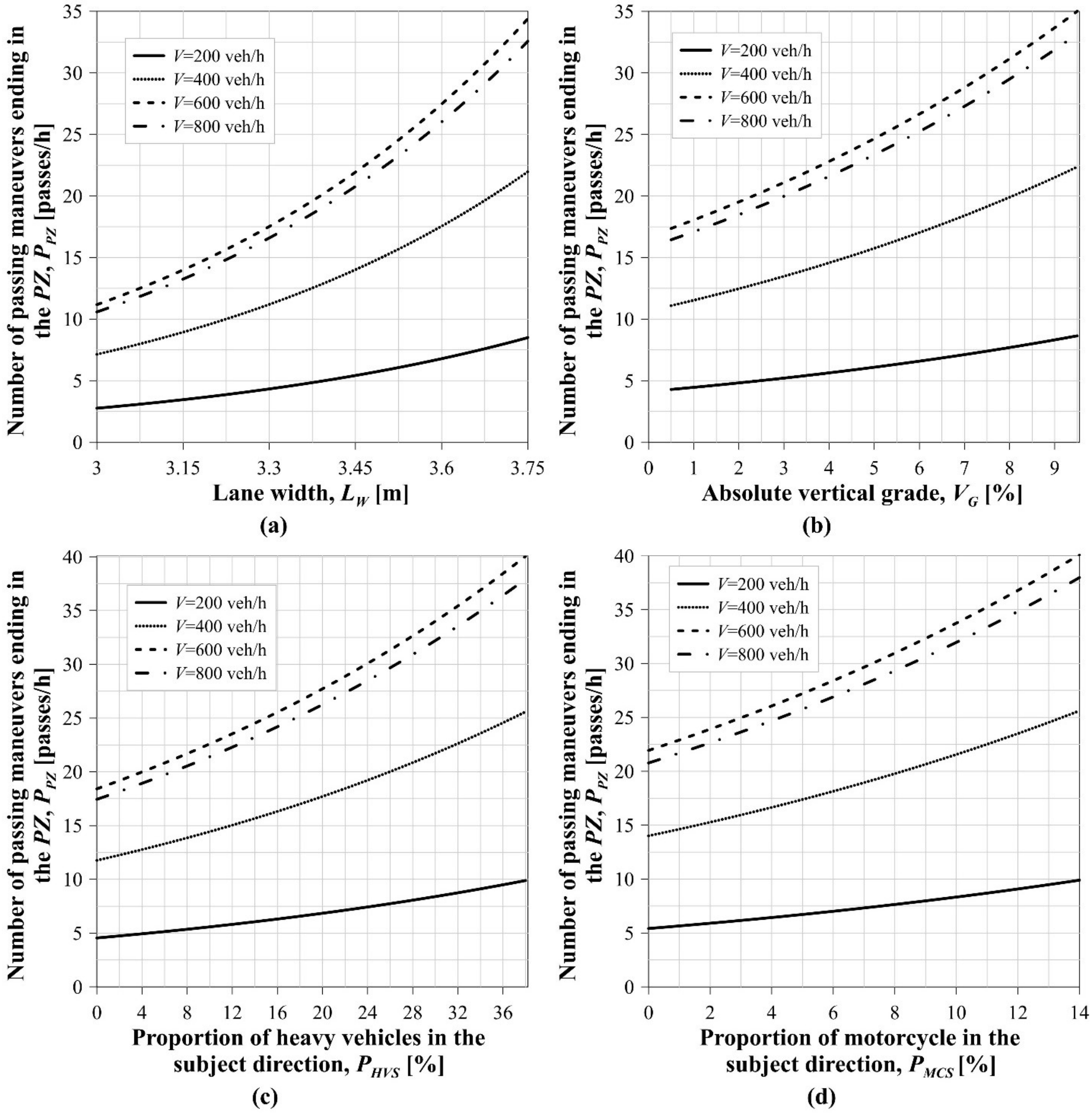

Figure 4: Effects of explanatory variables of Model 1 on the P_{PZ}

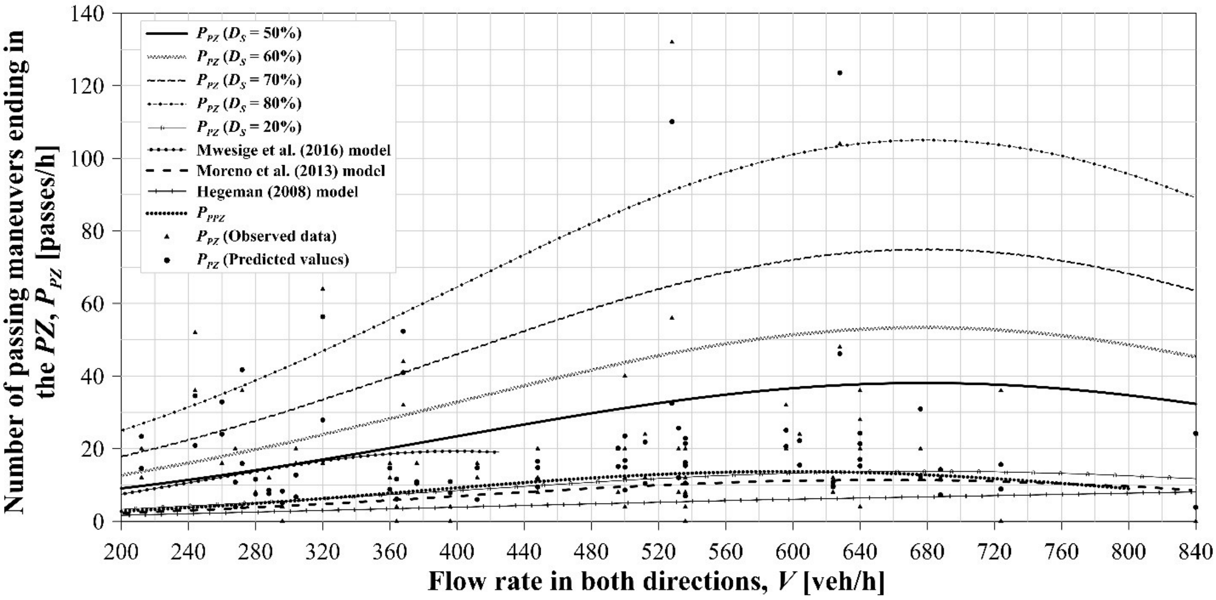

Figure 5: Effect of the flow rate in both directions on the passing rate and comparison of this study's models and previous works

Table 1: List of existing studies and their corresponding contributions (e.g., explanatory variables) and shortcomings

Studies	Explanatory variables													Shortcomings
	V_S	V_O	V	$\bar{\mu}_s$	σ_s	$P(g>30)$	$P(road)$	L_{PZ}	D_S	V_G	S_{85}	P_{HV}	$\boldsymbol{k}$	
Wardrop (1952)	*			*	*									A theoretical model
Daganzo (1975)			*											A theoretical model
McLean (1989)						*	*							A theoretical model
Dommerholt and Botma (1988)	*	*	*		*								*	A theoretical model
Tuovinen and Enberg (2006)	*													Using a linear regression model
Hegeman (2008)	*	*												Using a linear regression model
Moreno et al. (2013)			*					*	*					
Mwesige et al. (2016)			*					*	*	*	*	*		

V_S = traffic flow in the subject direction [veh/h]

V_O = traffic flow in the opposite direction [veh/h]

V = traffic flow in both direction [veh/h]

$\bar{\mu}_s$ = average of space mean speeds [km/h]

σ_s = standard deviation of space mean speed [km/h]

$P(g>30)$ = proportion of time that there is a gap larger than the critical gap (30 s)

$P(road)$ = proportion of road length suitable for passing

L_{PZ} = length of PZ [*m*]

D_S = directional split in the subject direction [%]

V_G = absolute vertical grade [%]

S_{85} = 85th percentile speed [km/h]

P_{HV} = proportion of heavy vehicles [%]

k = density of vehicles [*pc/km*]

Table 2: Geometric characteristics of the PZs and total number of observed passing maneuvers at each site for 15-min periods in each direction

PZ ID	Highway (*)	Length	Width	Shoulder width	Absolute vertical grade	Posted speed limit	Passing maneuvers recorded	15-min period observations
		[m]	[m]	[m]	[%]	[Km/h]	[#]	[#]
1	JF	225	3.45	-	0.85	85	73	16
2	JF	309	3.45	-	0.58	85	58	14
3	JF	180	3.25	-	1.1	85	24	10
4	JF	204	3.25	-	2.5	85	17	8
5	JB	164	3.00	-	5.5	95	15	4
6	JB	231	3.00	-	3.5	95	18	8
7	JK	345	3.75	1.2	9.5	85	174	16

(*) JF = Jiroft-Faryab, JB = Jiroft-Baft, and JK = Jiroft-Kerman

Table 3: Descriptive statistics of explanatory variables

Variable (Unit)	Mean	Min.	Max.	Confidence interval (95%)
Number of passing maneuvers ending in PZ in the subject direction, N_{PZ} (Passes per 15 min)	5.0	0	33	(3.8, 6.2)
Number of passing maneuvers starting and ending in PZ in subject direction, N_{PPZ} (Passes per 15 min)	2.3	0	21	(1.5, 3.1)
PZ length, L_{PZ} (m)	254.60	164	345	(240.2, 269.0)
Upstream NPZ length, L_{UNPZ} (m)	1265.5	130	5010	(946.4, 1584.6)
Lane width, L_W (m)	3.39	3.00	3.75	(3.34, 3.45)
Absolute vertical grade, V_G (%)	3.4	0.6	9.5	(2.6, 4.1)
Flow rate in both directions, V (veh/h)	470.4	212	840	(434.6, 506.3)
Flow rate in the subject direction, V_S (veh/h)	235.2	80	648	(212.7, 257.8)
Flow rate in the opposite direction, V_O (veh/h)	235.2	80	648	(212.7, 257.8)
Directional split of traffic volume, D_S (%)	50	22.9	77.1	(47.6, 52.4)
Proportion of heavy vehicles in both directions, P_{HV} (%)	8.2	0	30.2	(6.4, 10.1)
Proportion of heavy vehicles in the subject direction, P_{HVS} (%)	8.6	0	37.9	(6.4, 10.8)
Proportion of motorcycle in the subject direction, P_{MCS} (%)	3.0	0	13.9	(2.2, 3.7)
Mean free-flow speed, M_{FFS} (km/h)	85.3	63.7	102.0	(83.7, 87.0)
Standard deviation of free-flow speed, σ_s (km/h)	16.0	9.5	27.6	(15.1, 16.9)
85^{th} Percentile free-flow speed, S_{85} (km/h)	101.3	71.0	129.4	(99.1, 103.4)

Table 4: Estimated Poisson model parameters (Model 1 predicts N_{PZ}, Model 2 predicts N_{PPZ})

variables	Model 1		Model 2	
	β-Estimate	Z-value	β-Estimate	Z-value
L_{PZ}	-	-	0.00786	2.69[b]
L_W	1.4989	3.82[a]	1.71082	2.08[c]
V_G	0.0779	2.99[b]	0.06994	2.04[c]
V	0.00852	3.39[b]	0.01218	3.00[b]
V^2	-6.28×10^{-6}	-2.41[c]	-10.2×10^{-6}	-2.31[c]
D_S	0.03381	6.19[a]	0.02636	4.55[a]
P_{HVS}	0.02044	2.00[c]	-	-
P_{MCS}	0.04307	1.78[d]	-	-
constant	-8.4586	-7.44[a]	-12.31318	-5.20[a]
Test	χ^2	p-value	χ^2	p-value
Overall model evaluation				
Likelihood ratio test	226.73	0.0000	208.69	0.0000
Goodness-of-fit				
Deviance test	86.925	0.061	90.559	0.042
Pearson test	74.03	0.288	84.488	0.099
	$\bar{\chi}^2$	p-value	$\bar{\chi}^2$	p-value
Overdispersion				
LR test of α	0.00000	0.500	0.09	0.379
Random-effects				
LR test of φ	0.00	1.00	0.00	1.00
Cragg-Uhler R^2	0.950		0.939	
McFadden's R^2	0.418		0.479	
Sample size	76		76	

([a]) significance level at 0.001. ([b]) significance level at 0.01. ([c]) significance level at 0.05. ([d]) significance level at 0.1.

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Table 5: Average marginal effects of explanatory variables on the number of passing maneuvers ending in PZ per 15 minutes [passes/15-min/one-unit change in variable]

Variables	Average marginal effects	Confidence interval (95%)
L_W	7.47	(3.57, 11.38)
V_G	0.39	(0.13, 0.65)
D_S	0.17	(0.11, 0.22)
P_{HVS}	0.10	(0.001, 0.20)
P_{MCS}	0.21	(-0.022, 0.45)

Table 6: Average marginal effects of explanatory variables on the number of passing maneuvers that start and end in PZ per 15 minutes [passes/15-min/one-unit change in variable]

Variables	Average marginal effects	Confidence interval (95%)
L_{PZ}	0.018	(0.004, 0.031)
L_W	3.92	(0.17, 7.66)
V_G	0.16	(0.004, 0.316)
D_S	0.06	(0.033, 0.088)