

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

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

3

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16

17 **Abstract**

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

30

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

## 33 **1. Introduction**

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

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

51 Harwood, et al. (2008) presented two categories for the PZs: short PZs (PZ lengths shorter  
52 than 240 m) and long PZs (PZ lengths equal to 300 m or more). Using traffic simulation analysis,  
53 they showed that very few passing maneuvers occurred in short PZs. Their field observations also  
54 showed that only 0.4% of all vehicles made passing maneuvers in short PZs while 92% of passing  
55 maneuvers ended in no-passing zones (NPZ). Hence, their conclusion that short PZs contribute

56 little to operational efficiency. However, they did not develop the passing rate prediction model  
57 for PZs. While a few field studies investigated the passing rate models (Mwesige, et al., 2016,  
58 Moreno, et al., 2013, Hegeman, 2008), none of them considered short PZs in their analysis.  
59 Furthermore, the effects of two explanatory variables - lane width and proportion of motorcycles  
60 on the passing rate - were not investigated in previous works.

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

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

75

## 76 **2. Background**

77 Wardrop (1952) offered a theoretical model to estimate passing demand from the speed  
78 distribution while assuming an ideal situation with no opposing traffic and no passing sight

79 limitations. He used eq.(1) to calculate the number of passing maneuvers per kilometer per hour  
80 ( $P_n$ ):

$$81 \quad P_n = 5.6 \left( \frac{V_S^2 \cdot \sigma_s}{\bar{\mu}_s^2} \right) \quad (1)$$

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

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

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

$$89 \quad P(o.t) = P(g > 30) \times P(road) \quad (2)$$

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

96 Dommerholt and Botma (1988) attempted to capture both passing opportunities and  
97 passing demand for the development of a passing rate model. They developed the theoretical  
98 passing rate as a function of the standard deviation of the speed and the density of vehicles. To  
99 calculate the *expected number of overtaking maneuvers*, they reduced the theoretical passing rate  
100 using the probability that the passing maneuver was possible. To verify their proposed model,

101 Dommerholt and Botma (1988) investigated six locations. Real passing rates were lower than the  
 102 values obtained from the Dommerholt and Botma equation. To reduce the theoretical passing rate,  
 103 they took the following two factors into account: (1) that the passing maneuver does not occur if  
 104 the speed difference between the lead and following vehicles is below a threshold value, and (2)  
 105 that the passing rate reduces linearly with increasing mean platoon length for traffic flows above  
 106 400 veh/h.

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

$$115 \quad OF = 1.6 \times 10^{-11} \times V_s^{1.5} (1700 - V_o)^{2.5} \quad (3)$$

116 where  $OF$  is the passing rate per kilometer per hour,  $V_s$  is traffic flow in the analysis direction  
 117 [veh/h],  $V_o$  is traffic flow in the opposite direction [veh/h].

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

$$120 \quad PF = \exp \left( \begin{array}{l} -4.57904 - 0.00125 \cdot V^2 - 0.0000013 \cdot L_{PZ}^2 \\ + 2.75645 \cdot D_s + 0.04093 \cdot V + 0.003455 \cdot L_{PZ} \end{array} \right) \quad (4)$$

121 where  $V$  is the two-way traffic volume for a 15-min period [veh/h],  $L_{PZ}$  is the length of PZ [m],  
 122 and  $D_s$  is the directional split in the subject direction. They used two different road segments with

123 different lengths of PZ in two directions and used 114 periods of 15 min per passing zone to  
124 develop their model. The maximum passing rate occurred at a two-way traffic volume between  
125 600 and 700 veh/h for all PZs.

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

$$128 \quad P = \exp \left( \begin{array}{l} -5.089 + 1.123 \cdot L_{PZ} - 0.1948 \cdot L_{PZ}^2 + 0.09951 \cdot V_G \\ + 0.01917 \cdot V - 0.00002401 \cdot V^2 + 0.008177 \cdot S_{85} \\ + 0.0376 \cdot D_S + 0.05555 \cdot P_{HV} + 0.0008065 \cdot P_{HV}^2 \end{array} \right) \quad (5)$$

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

132 Mwesige, et al. (2016) used a total of 96 observations to estimate their models. They found  
133 that by increasing the percentage of heavy vehicles, the passing rate rose, then reached a peak of  
134 35% before falling back. Based on their model, passing capacity occurred at the two-way volume  
135 of 400 veh/h. Other variables including the length of PZ, absolute vertical grade, and directional  
136 split in the subject direction were significant at the 95% confidence level. The 85<sup>th</sup> percentile speed  
137 was significant at the 90% confidence level. Table 1 presents a list of the above-mentioned studies  
138 and their corresponding contributions (e.g., explanatory variables) and shortcomings.

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

142

### 143 **3. Objectives, methodology, and data collection**

#### 144 **3.1 Objectives**

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

152

#### 153 **3.1. Variables**

##### 154 **3.1.1 Dependent variable**

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

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

167

### 168 **3.1.2 Explanatory variables**

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

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

178

### 179 **3.2. Statistical analysis**

180 The number of passing maneuvers takes only non-negative integer values. Thus, in this case, the  
181 count data models provide an appropriate framework for estimating the number of passing  
182 maneuvers. Poisson regression is the most popular method for modeling count data. In the Poisson  
183 regression model, the probability of observation  $i$ -th having  $y_i$  completed passing maneuvers in  
184 15-min, is given by:

$$185 \quad P(y_i) = \frac{\exp(-\lambda_i)\lambda_i^{y_i}}{y_i!} \quad (6)$$

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

$$190 \quad \lambda_i = E[y_i] = VAR[y_i] = \exp(\beta X_i) \quad (7)$$

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

$$194 \quad L(\beta) = \prod_i \frac{\exp[-\exp(\beta X_i)] [\exp(\beta X_i)]^{y_i}}{y_i!} \quad (8)$$

195 The equality between mean and variance represents a limitation in the case of  
 196 over-dispersed data (i.e., when the variance is greater than the mean). In many studies, the omitted  
 197 variables are the main reason for overdispersion (Washington, et al., 2010). Overdispersion leads  
 198 to inflation in estimated standard errors of estimated parameters, but it does not affect the  
 199 magnitude of estimated parameters (Cameron and Trivedi, 2013). The Negative Binomial model  
 200 is able to account for overdispersion, which is derived by rewriting Equation (7) into Equation (9)  
 201 :

$$202 \quad \lambda_i = \exp(\beta X_i + \varepsilon_i) \quad (9)$$

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

$$205 \quad VAR[y_i] = E[y_i] + \alpha E[y_i]^2 = \lambda_i + \alpha \lambda_i^2 \quad (10)$$

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

$$209 \quad P(y_i) = \frac{\Gamma((1/\alpha) + y_i)}{\Gamma(1/\alpha) y_i!} \left( \frac{1/\alpha}{(1/\alpha) + \lambda_i} \right)^{1/\alpha} \left( \frac{\lambda_i}{(1/\alpha) + \lambda_i} \right)^{y_i} \quad (11)$$

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

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

$$217 \quad Ln(\lambda_{ij}) = \beta X_{ij} + \eta_j \quad (12)$$

218 where  $\lambda_{ij}$  is the expected number of completed passing maneuvers for the  $i$ -th 15-min belonging to  
 219  $j$ -th PZ,  $X_{ij}$  is a vector of explanatory variables,  $\beta$  is a vector of corresponding parameters, and  $\eta_j$   
 220 is a random effect for observations of the  $j$ -th PZ. Based on this specification, the random-effects  
 221 Poisson model is:

$$222 \quad P(y_{ij} | X_{ij}, \eta_j) = \frac{\exp[-\exp(\beta X_{ij}) \exp(\eta_j)] [\exp(\beta X_{ij})]^{y_{ij}}}{y_{ij}!} \quad (13)$$

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

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

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

231

### 232 **3.3. Study sites and data collection**

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

240 Data were collected using a Phantom 4 Pro drone (Figure 2) equipped with a 1-inch  
241 20-megapixel sensor capable of shooting 4K/60fps video and a 3-axis gimbal to stabilize the  
242 camera oscillation. During video recording, the minimum altitude of the drone was 150 m to avoid  
243 any impact on driver behavior. Data were collected during 38 flights lasting 15-20 minutes each.  
244 The weather conditions during data collecting were clear and good.

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

250 Geometry variables such as lane width, vertical grade, and PZ length were measured in the field.

251 The hourly flow rate was calculated as the volume of vehicles in 15 minutes multiplied by four.

252

#### 253 **4. Results**

254 Table 3 presents a summary of the observed variables at the PZs. The average number of passing

255 maneuvers ending in the PZ in the subject direction ( $N_{PZ}$ ) was 5.0 passes per 15 minutes, reaching

256 a maximum value of 33 passes per 15 minutes. The average and maximum values of the number

257 of passing maneuvers starting and ending in PZ in the subject direction ( $N_{PPZ}$ ) were 2.3 and 21,

258 respectively. The average of  $N_{PZ}$  was more than two times that of  $N_{PPZ}$ , which means that more

259 than half of the drivers ending their maneuver in PZ, started it from NPZ. The flow rate in both

260 directions had a range between 212 and 840 veh/h, with a directional split up to 80%, which

261 provides a suitable combination for analysis. The directional split equals 30% means ( $V_S = 0.3V$ ,

262 and  $V_O = 0.7V$ ). The proportion of motorcycles in the subject direction had a maximum value of

263 14%, which was a considerable one for rural highways. Mean free-flow speed for every 15 minutes

264 had an average of 85.3 km/h with an average standard deviation of 16.0 km/h. Based on the

265 explanatory variables presented in Table 3, the  $N_{PZ}$  and  $N_{PPZ}$  are estimated using count data models.

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

279

#### 280 **4.1. Estimating $N_{PZ}$ (Model 1)**

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

289 Variables of the PZ length, upstream NPZ length, 85<sup>th</sup> Percentile free-flow speed, and  
290 standard deviation of free-flow speed were statistically not significant at the confidence level of  
291 90% and, therefore, removed from the model. However, the signs of the coefficients for these  
292 variables were consistent with a priori expectation. The lane width was found to be highly  
293 significant ( $p$ -value  $< 0.001$ ). Its positive sign implies that an increase in lane width leads to an  
294 increase in the passing rate. Table 5 shows that the average marginal effect of lane width on passing  
295 rate at 15 min is equal to 7.47, which means that if the lane width increases by 0.2 m,  $N_{PZ}$  increases  
296 by 6 passes per hour on average. The marginal effect of lane width increases by increasing its  
297 value. The absolute vertical grade was statistically significant at the 95% confidence level ( $p$ -value  
298  $< 0.01$ ). Based on its marginal effect reported in Table 5, each 1% increase in the absolute vertical  
299 grade, the  $N_{PZ}$  increases by the hourly passing rate of 1.56 passes on average.

300 The flow rate in both directions ( $V$ ) and its quadratic term had a significant effect at the  
301 95% confidence level ( $p$ -values  $< 0.05$ ). This variable has different effects based on its value.  
302 Figure 3 illustrates the average marginal effects of flow rate in both directions on  $N_{PZ}$  for different  
303 values of the flow rate. This figure shows that the positive marginal effect peaked at the flow rate  
304 of 400 veh/h. The figure shows a sharp fall in the marginal effect of flow rate such that it was zero  
305 at the flow rate of 680 veh/h. From this value, the effect of flow rate on  $N_{PZ}$  was negative, which  
306 means that at an increased flow rate (greater than 680 veh/h), the passing rate decreased. The  
307 directional split of traffic volume ( $D_S$ ) was also a significant variable at the level of 0.001. With  
308 an increase in  $D_S$ , the traffic in the subject direction increases and the traffic in the opposite  
309 direction decreases, with the former resulting in an increase in the passing demand, and the latter  
310 leading to an increase in passing opportunities. Another way to capture this effect in the models is  
311 to use the two variables of the flow rate in the subject and flow rate in the opposite direction.

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

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

320

#### 321 **4.2. Estimating $N_{PPZ}$ (Model 2)**

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

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

331

### 332 **5. Discussion**

333 The upstream NPZ length did not have a significant effect on the passing rate. Mwesige, et al.  
334 (2016) reached a similar result on the effectiveness of the upstream NPZ length. They presented

335 four factors that could explain this result. The two variables of 85<sup>th</sup> percentile free-flow speed and  
 336 standard deviation of free-flow speed, like the study of Mwesige, et al. (2016), were statistically  
 337 not significant at the 95% confidence level.

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

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

$$352 \quad P_{PZ} = 4 \cdot N_{PZ} = 4 \cdot \exp \left( \begin{array}{l} -8.4586 + 1.4989 \cdot L_W + 0.0779 \cdot V_G + 0.00852 \cdot V - 6.28 \times 10^{-6} \cdot V^2 \\ + 0.03381 \cdot D_S + 0.02044 \cdot P_{HVS} + 0.04307 \cdot P_{MCS} \end{array} \right) \quad (14)$$

$$353 \quad P_{PPZ} = 4 \cdot N_{PPZ} = 4 \cdot \exp \left( \begin{array}{l} -12.31318 + 0.00786 \cdot L_{PZ} + 1.71082 \cdot L_W + 0.06994 \cdot V_G \\ + 0.01218 \cdot V - 10.2 \times 10^{-6} \cdot V^2 + 0.02636 \cdot D_S \end{array} \right) \quad (15)$$

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

356 Figure 4a provides information on the change in the passing rate of maneuvers ending in  
357 the PZ ( $P_{PZ}$ ) for different values of the lane width at four different levels of the traffic flow rate  
358 (200, 400, 600, and 800 veh/h). The results show that by increasing the lane width, the passing rate  
359 increased. The marginal effect of lane width increased as the base value increased. For example,  
360 adding 0.1 m to a lane with 3.6 m width (base value) has more effect on the passing rate than  
361 adding 0.1 m to a lane with 3 m width. A wider lane width results in drivers taking more risks  
362 because it provides more room for passing and helps to prevent opposing vehicles from colliding.  
363 Furthermore, the marginal effect of lane width with respect to the flow rate is maximized at the  
364 traffic flow rate equal to 680 veh/h. Lane width had a highly significant effect in both Model 1 and  
365 Model 2. This variable was not evaluated in previous works because their PZs had the same lane  
366 width.

367 Figure 4b shows the effect(s) of absolute vertical grade on  $P_{PZ}$  at traffic flow rate levels of  
368 200, 400, 600, and 800 veh/h. Unlike previous studies (Mwesige, et al., 2016, Moreno, et al., 2013,  
369 Hegeman, 2008) where sites were located on flat terrain, in this study the absolute vertical grade  
370 had a wide range from 0.58 to 9.5%. The results show that absolute vertical grade had a positive  
371 impact on the passing rate, and the impact had a peak respect to the traffic flow rate. The vertical  
372 grade reduces the speed of heavy vehicles, which causes the platoons. To consider this impact,  
373 HCM used an adjusted factor to calculate the demand flow rate (TRB, 2010).

374 Figure 4c shows the rise in the passing rate in the subject direction ( $P_{PZ}$ ) caused by an  
375 increase in the proportion of heavy vehicles in the subject direction ( $P_{HVS}$ ). Mwesige, et al. (2016)  
376 used the proportion of heavy vehicles in both directions ( $P_{HV}$ ); however, this variable did not have  
377 a significant effect on the  $P_{PZ}$ . As the percentage of heavy vehicles in the subject direction  
378 increases, the number of platoons and their length grow, which increases the frustration and desire

379 of drivers behind to pass (Penmetsa, et al., 2015, Polus and Cohen, 2009). Hence,  $P_{HVS}$  better  
380 explains the effect of the proportion of heavy vehicles on the passing rate in the subject direction  
381 than the  $P_{HV}$ . By increasing the  $P_{HVS}$ , the platooning and PTSF will increase, which leads to an  
382 increase in the demand for passing maneuvers. Drivers caught in a platoon behind slow vehicles  
383 (heavy vehicles for example) will attempt to conduct more passing maneuvers. The ability to pass  
384 is provided by the PZs if and when drivers find a gap in the opposite direction. Mwesige, et al.  
385 (2016) showed that the passing rate increases with the  $P_{HV}$  to a peak at 35% and then decreases. In  
386 this study, the highest levels of  $P_{HV}$  and  $P_{HVS}$  are 30.2 and 37.9%, respectively, and the results  
387 show an increase in the passing rate with an increase in  $P_{HVS}$  consistently with Mwesige, et al.  
388 (2016). The  $P_{HVS}$  did not have a significant effect on the number of passing maneuvers that start  
389 and end in the NPZ ( $P_{PPZ}$ ). It is for this reason that, as observed in the recorded videos, the platoon  
390 discharges before the PZs, hence, most of the vehicles in the platoon start passing maneuvers in  
391 the NPZ.

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

398 It should be noted that high-speed motorcycles are forbidden in Iran. Hence, this variable  
399 might prove to be insignificant in other countries. In fact, in the study conducted by Hegeman  
400 (2008), motorcycles accounted for less than 2% of traffic flow, and they did not consider this  
401 variable in their model. Similarly, other previous studies did not evaluate the effect of the

402 proportion of motorcycles on the passing rate. Figure 5 illustrates the graphs of the passing rate in  
403 the subject direction and the traffic flow rate in both directions. Figures 4 was produced for  $V_G =$   
404 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  
405 be consistent with studies conducted by Mwesige, et al. (2016) and Moreno, et al. (2013) and make  
406 it possible for comparing. The graphs of  $P_{PZ}$  were plotted at five directional split levels of 20, 50,  
407 60, 70, and 80%.

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

420 The models proposed by Hegeman (2008) and Moreno, et al. (2013) (Equation (3) and (4))  
421 underestimated the passing rate. Their studies were carried out in developed countries, which  
422 might explain the significant differences between passing rate values in their work and that of  
423 Mwesige, et al. (2016). Another reason for the lower prediction by Hegeman (2008) is due to the  
424 *Dutch Sustainable Safety Program*, which recommended that authorities design two-lane

425 highways along which passing is prohibited, even where there is sufficient sight distance. In the  
426 study of Moreno, et al. (2013), the two studied PZs were too close to each other (less than 350 m),  
427 hence a reduction in the passing rate was possible.

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

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

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

443 Figure 5 shows the passing capacity for maneuvers that start and end in the PZ ( $P_{PPZ}$ ) at  
444 the flow rate of 597 veh/h. Moreno, et al. (2013) found that the peak passing rate occurred at  
445 600-700 veh/h, which is similar to the findings of this research. However, in the study conducted  
446 by Mwesige, et al. (2016), the passing rate reached its capacity at the flow rate in both directions  
447 at 400 veh/h. The maximum flow rate that they observed in their study was 426 veh/h. Hence,

448 they could not estimate the effect of superior levels of flow rate on the passing rate. They stated  
449 that it was not possible to observe the passing capacity at 600 veh/h because the average  
450 headways were too short (Mwesige, et al., 2016). However, it should be noted that by increasing  
451 the flow rate, the platoons will increase and, commonly, several drivers in the platoons use a  
452 single gap in the opposite direction to pass the slow vehicle together.

453

## 454 **6. Conclusion**

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

458 The main conclusions of the study were as follows:

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

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

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

487           Heavy vehicles travel at a slower speed than passenger cars, and their speed decreases  
488 further as the absolute vertical grade increases. The result of this work showed that an increment  
489 in the proportion of heavy vehicles and/or the absolute vertical grade increases the passing rate.  
490 However, the passing maneuver is a demanding and dangerous task, so planners and designers  
491 should consider the safety implications of the proportion of heavy vehicles and vertical grades  
492 when deciding between two-lane highways and other facility types. To achieve more homogenous

493 speeds, lower vertical grades have to be assumed at the design stage if a high percentage of heavy  
494 vehicles is expected.

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

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

507

## 508 **Data Availability Statement**

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

511

## 512 **Acknowledgment**

513 This research was funded by Tarbiat Modares University.

## 514 **Notation list**

515  $D_S$  = directional split of traffic volume

- 516  $L_{PZ}$  = passing zone length
- 517  $L_W$  = lane width
- 518  $N_{PPZ}$  = number of passing maneuvers per 15 minutes starting and ending in PZ in subject
- 519 direction
- 520 NPZ = no-passing zone
- 521  $N_{PZ}$  = number of passing maneuvers per 15 minutes ending in the passing zone (PZ) in the
- 522 subject direction
- 523  $P_{HV}$  = proportion of heavy vehicles in both directions
- 524  $P_{HVS}$  = proportion of heavy vehicles in the subject direction
- 525  $P_{MCS}$  = proportion of motorcycles in the subject direction
- 526  $P_{PPZ}$  = number of passing maneuvers per hour starting and ending in PZ in subject direction
- 527  $P_{PZ}$  = number of passing maneuvers per hour ending in the passing zone (PZ) in the subject
- 528 direction
- 529 PTSF = percent time spent following
- 530 PZ = passing zone
- 531  $V$  = flow rate in both directions
- 532  $V_G$  = absolute vertical grade
- 533  $V_O$  = flow rate in the opposite direction
- 534  $V_S$  = flow rate in the subject direction

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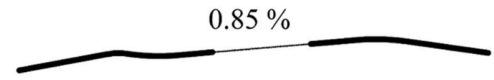
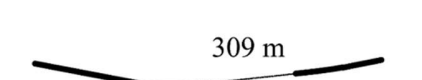
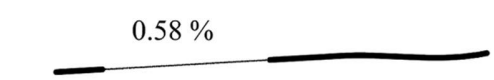
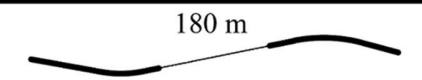
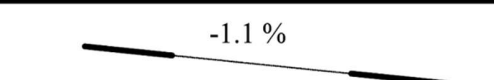
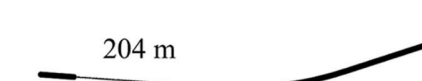

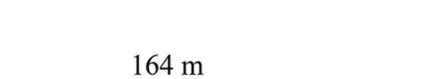





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598

599 List of Figures:

<b>PZ ID</b>	<b>Alignment</b>	<b>Profile</b>
<b>1</b>	 <p>225 m</p>	 <p>0.85 %</p>
<b>2</b>	 <p>309 m</p>	 <p>0.58 %</p>
<b>3</b>	 <p>180 m</p>	 <p>-1.1 %</p>
<b>4</b>	 <p>204 m</p>	 <p>-2.5 %</p>
<b>5</b>	 <p>164 m</p>	 <p>-5.5 %</p>
<b>6</b>	 <p>231 m</p>	 <p>-3.5 %</p>
<b>7</b>	 <p>345 m</p>	 <p>9.5 %</p>

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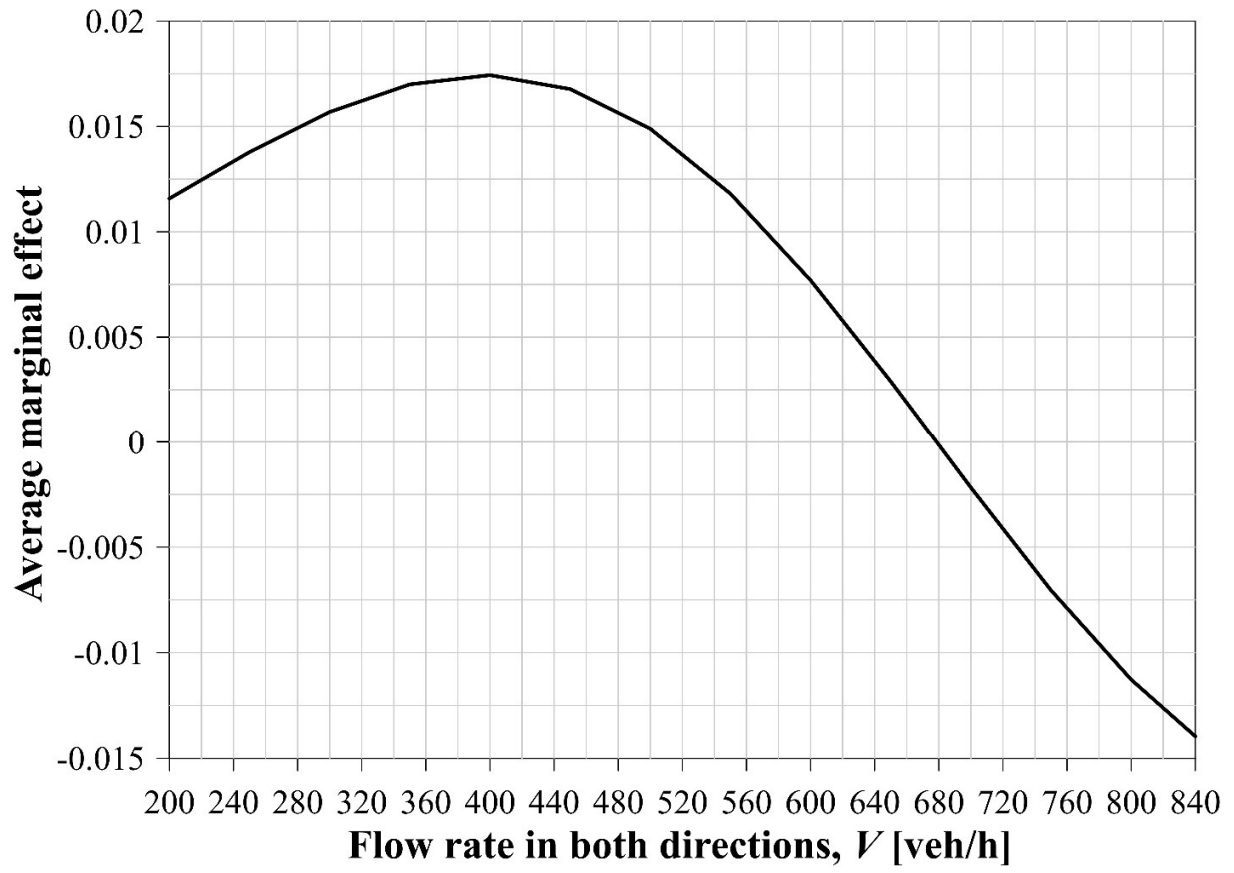
601 **Figure 1: Diagrams of the horizontal and vertical alignment around the PZs**



602

603 **Figure 2: Phantom 4 Pro drone**

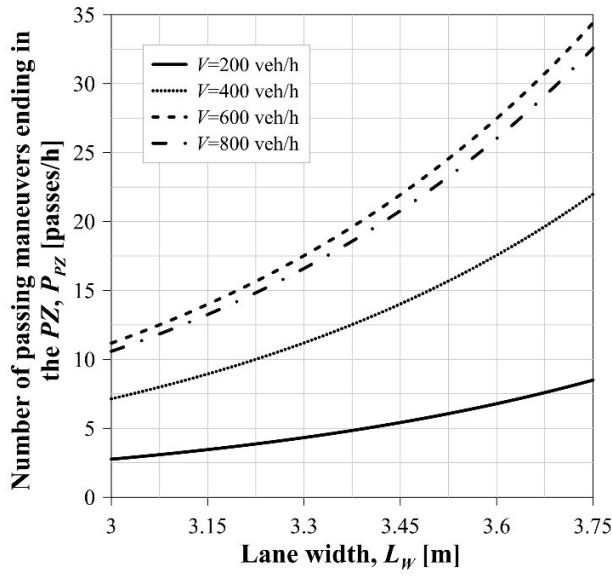
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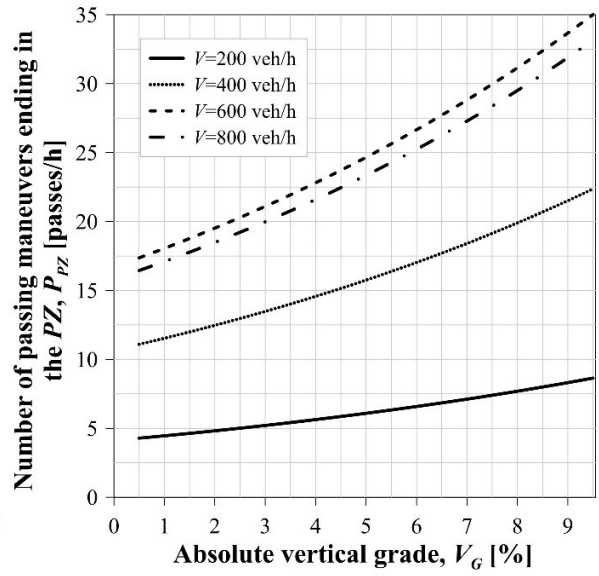
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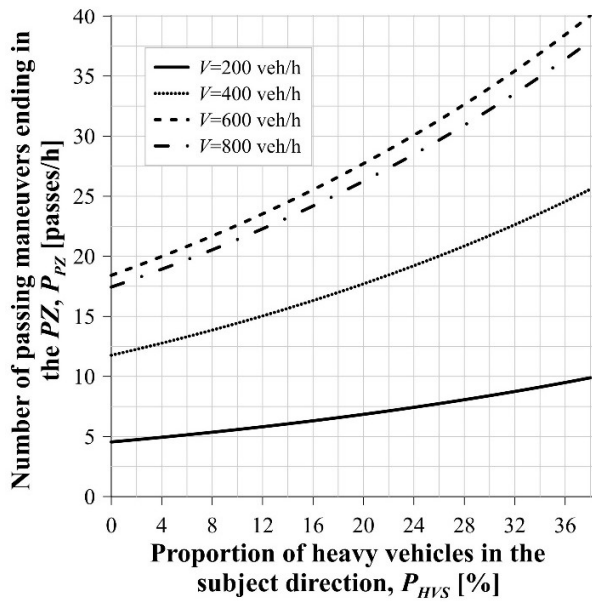
**Figure 3: The average marginal effects of the flow rate in both directions on NPZ**



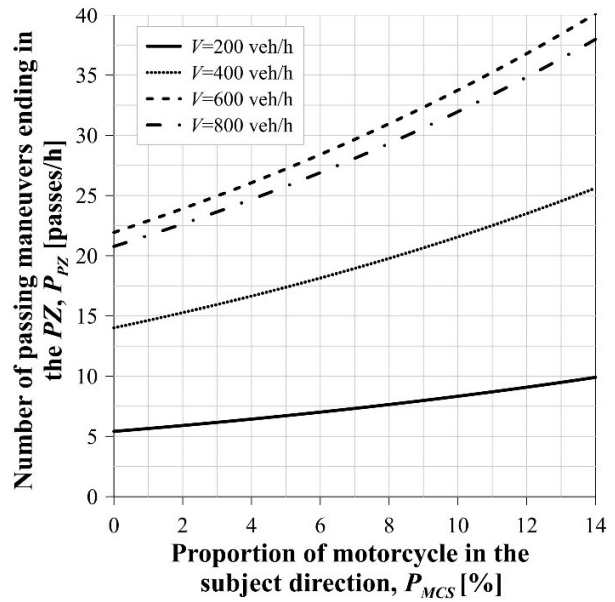
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(b)



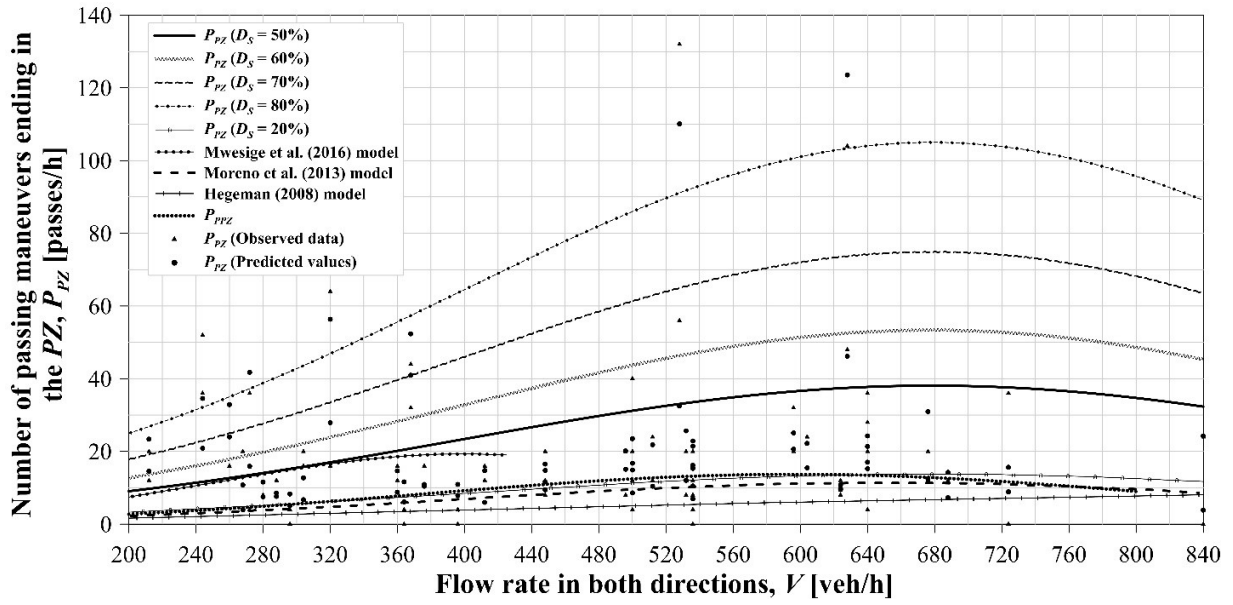
(c)



(d)

607

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



609

610 **Figure 5: Effect of the flow rate in both directions on the passing rate and comparison of this**

611 **study's models and previous works**

612

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

Studies	Explanatory variables												Shortcomings	
	$V_S$	$V_O$	$V$	$\bar{\mu}_s$	$\sigma_s$	$P(g>30)$	$P(road)$	$L_{PZ}$	$D_S$	$V_G$	$S_{85}$	$P_{HV}$		$k$
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]								$P(road)$ = proportion of road length suitable for passing						
$V_O$ = traffic flow in the opposite direction [veh/h]								$L_{PZ}$ = length of PZ [m]						
$V$ = traffic flow in both direction [veh/h]								$D_S$ = directional split in the subject direction [%]						
$\bar{\mu}_s$ = average of space mean speeds [km/h]								$V_G$ = absolute vertical grade [%]						
$\sigma_s$ = standard deviation of space mean speed [km/h]								$S_{85}$ = 85 <sup>th</sup> percentile speed [km/h]						
$P(g>30)$ = proportion of time that there is a gap larger than the critical gap (30 s)								$P_{HV}$ = proportion of heavy vehicles [%]						
								$k$ = density of vehicles [pc/km]						

615

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

<b>PZ ID</b>	<b>Highway (*)</b>	<b>Length</b>	<b>Width</b>	<b>Shoulder width</b>	<b>Absolute vertical grade</b>	<b>Posted speed limit</b>	<b>Passing maneuvers recorded</b>	<b>15-min period observations</b>
		<b>[m]</b>	<b>[m]</b>	<b>[m]</b>	<b>[%]</b>	<b>[Km/h]</b>	<b>[#]</b>	<b>[#]</b>
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

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

619

620 **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, $\sigma_s$ (km/h)	16.0	9.5	27.6	(15.1, 16.9)
85 <sup>th</sup> Percentile free-flow speed, $S_{85}$ (km/h)	101.3	71.0	129.4	(99.1, 103.4)

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

variables	Model 1		Model 2	
	$\beta$ -Estimate	Z-value	$\beta$ -Estimate	Z-value
$L_{PZ}$	-	-	0.00786	2.69 <sup>b</sup>
$L_W$	1.4989	3.82 <sup>a</sup>	1.71082	2.08 <sup>c</sup>
$V_G$	0.0779	2.99 <sup>b</sup>	0.06994	2.04 <sup>c</sup>
$V$	0.00852	3.39 <sup>b</sup>	0.01218	3.00 <sup>b</sup>
$V^2$	$-6.28 \times 10^{-6}$	-2.41 <sup>c</sup>	$-10.2 \times 10^{-6}$	-2.31 <sup>c</sup>
$D_S$	0.03381	6.19 <sup>a</sup>	0.02636	4.55 <sup>a</sup>
$P_{HVS}$	0.02044	2.00 <sup>c</sup>	-	-
$P_{MCS}$	0.04307	1.78 <sup>d</sup>	-	-
<i>constant</i>	-8.4586	-7.44 <sup>a</sup>	-12.31318	-5.20 <sup>a</sup>
Test	$\chi^2$	<i>p</i> -value	$\chi^2$	<i>p</i> -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
	$\bar{\chi}^2$	<i>p</i> -value	$\bar{\chi}^2$	<i>p</i> -value
Overdispersion				
LR test of $\alpha$	0.00000	0.500	0.09	0.379
Random-effects				
LR test of $\varphi$	0.00	1.00	0.00	1.00
Cragg-Uhler R <sup>2</sup>	0.950		0.939	
McFadden's R <sup>2</sup>	0.418		0.479	
Sample size	76		76	

623 (<sup>a</sup>) significance level at 0.001. (<sup>b</sup>) significance level at 0.01. (<sup>c</sup>) significance level at 0.05. (<sup>d</sup>) significance level at 0.1.



625 **Table 5: Average marginal effects of explanatory variables on the number of passing maneuvers**  
 626 **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)

627

628 **Table 6: Average marginal effects of explanatory variables on the number of passing maneuvers**  
 629 **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)

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