1 **OPERATIONAL EFFECTIVENESS OF PASSING ZONES DEPENDING ON THEIR**
2 **LENGTH AND TRAFFIC VOLUME**
3
4 Corresponding Author:
5 **Ana Tsui Moreno**
6 Ph.D. Candidate
7 Highway Engineering Research Group
8 Universitat Politècnica de València
9 Camino de Vera, s/n. 46022 – Valencia. Spain
10 Tel: (34) 96 3877374
11 Fax: (34) 96 3877379
12 E-mail: anmoch@cam.upv.es
13
14 Other Authors:
15 **Carlos Llorca**
16 Ph.D. Candidate
17 Highway Engineering Research Group, Universitat Politècnica de València
18 Camino de Vera, s/n. 46022 – Valencia. Spain
19 Tel: (34) 96 3877374
20 Fax: (34) 96 3877379
21 E-mail: carlloga@cam.upv.es
22
23 **Alfredo García**
24 Professor
25 Highway Engineering Research Group, Universitat Politècnica de València
26 Camino de Vera, s/n. 46022 – Valencia. Spain
27 Tel: (34) 96 3877374
28 Fax: (34) 96 3877379
29 E-mail: agarciag@tra.upv.es
30
31 **Ana María Pérez-Zuriaga**
32 Ph.D.
33 Highway Engineering Research Group, Universitat Politècnica de València
34 Camino de Vera, s/n. 46022 – Valencia. Spain
35 Tel: (34) 96 3877374
36 Fax: (34) 96 3877379
37 E-mail: anpezu@tra.upv.es
38
39
40

1   **ABSTRACT**
2   Two-lane highways operation has been deeply studied. Most of the studies are focused on percentage
3   of following vehicles or the adjustment of the HCM procedure to local data. The HCM proposes the
4   length of no-passing zones as a parameter on the model; however, the distribution and characteristics
5   of the passing zones along the highway are not addressed. In fact, only a few studies on the expected
6   number of passes on a passing zone have been carried out.
7   This research presents an analysis of the effectiveness of passing zones considering their
8   length and traffic volume. Data were collected on four passing zones of one rural highway in Spain,
9   with two-way traffic volumes ranging from 100 vh/h to 900 vh/h and lengths between 265 and 1270
10   m. So, the influence of traffic flow on passing rates was calculated on the same passing zones. More
11   than 1,600 passing maneuvers were recorded during the 53 hours of observation on the scenarios.
12   Operational effectiveness of passing zones was obtained from passing frequency, as the
13   number of passes per time, and from passing rate, as the number of passes per time and following
14   vehicle. It was found that the longer the passing zone, the higher passing frequency. However, the
15   effectiveness of passing zones was stabilized from 1,100 m. On the other hand, balanced flows with
16   two-way traffic volumes between 600 and 700 veh/h optimized the number of passes. Nevertheless,
17   passing rate decreased as traffic volume increased. So, the increase in the passing frequency with the
18   traffic volume is lower than the increase of following vehicles.
19   The results were validated with additional 46-hour data from another twelve passing zones
20   with different lengths and traffic volumes.
21   Finally, Highway Capacity Manual adjustments on average travel speed and percentage time
22   spent following based on percentage of no-passing zones do not reliably represent effectiveness of
23   passing zones. Effectiveness of every passing zone should be considered instead.
24

1   **INTRODUCTION**
2
3   Two-lane highways have a level of interaction between vehicles traveling in the same and in opposing
4   direction that results in unique operational characteristics; mainly because faster vehicles that want to
5   travel at their desired speed face the on-coming traffic in the opposite lane and they may suffer delays
6   because of their inability to pass slow-moving vehicles. Thus, passing maneuvers are used by drivers
7   to relieve drivers stress, increase perceived level of service and reduce delay (*1*). On the other hand,
8   passes are conditioned by the opposing lane occupation which generates a conflict area. In fact, even
9   though passing is not one of the main causes of crashes in two-lane highways, its consequences are
10   severe (*2*).
11   From a traffic operation perspective, the limited passing opportunities result in higher impact
12   of slow-moving vehicles on traffic performance. The Highway Capacity Manual (HCM) utilizes the
13   percentage time spent following (PTSF) and the average travel speed (ATS) as major performance
14   indicators in two-lane highways (*3*). The effect of passes is reflected on the analysis procedure on
15   both PTSF, depending on the combined effect of directional distribution of traffic and of the
16   percentage of no-passing zones, and ATS, based on the percentage of no-passing zones.
17   In practice, PTSF is used as the indicator of platooning on two-lane highways; and refers to
18   the percentage of travel time a vehicle is trapped in a platoon being unable to pass slow-moving
19   vehicles. Many studies have been focused on PTSF and platooning (*4 - 9*), and they even developed
20   new methodologies for estimating performance on two-lane highways based on the average number of
21   headways inside and between platoons (*10*) and using speed and headways (*5, 11*). The 3-second
22   headway rule was used to estimate the percentage following in most operational studies (*4, 5, 6, 8, 12,*
23   *13*), as set on the HCM (*3*). However, other authors proposed 4 or 5 seconds (*7, 10, 14, 15, 16*). In
24   fact, it was confirmed that interaction between successive vehicles on the same lane generally
25   diminishes beyond a time headway threshold of 5-7 seconds (*6*). Besides, number of vehicles in
26   platoons increase as traffic volume increases (*10*). Consequently, there is not a uniform criterion on
27   the literature on following vehicles. PTSF is adjusted by the combined effect of the directional
28   distribution of traffic and of the percentage of no-passing zones (*3*): the PTSF increases as the
29   percentage of no-passing zones increases, for the same directional split; and it is maximum for a two-
30   way flow rate equal to 400 pc/h. As the traffic proportion is more favorable, its influence decreases.
31   On the other hand, larger percentage of no-passing zones decrease ATS (*3*), and it also
32   depends on the demand flow rate. The effect of no-passing zones on ATS on two-way segments is
33   maximum for two-way flow rate of 400 pc/h. However, Luttinen (*17*) pointed out that the adjustments
34   were obtained from simulations and no indications about the precision of the adjustment are given.
35   Morral and Werner (*18*) introduced the overtaking ratio for consideration as a measure of
36   service on two-lane highways. The overtaking ratio was defined as the achieved passes divided by
37   desired passes. The demand for passing was a function of the characteristics of drivers and vehicles
38   while the supply of passing depended on the percentage of no-passing zones and the distribution of
39   gaps in the opposing traffic stream. They stated that drivers' perception of level of service was based
40   on their ability or inability to pass slower vehicles; and that ability depended on the supply of
41   sufficient gaps in the opposing stream and sufficient sight distance; so, the overtaking ratio would
42   better represent drivers' perception. Their findings supported the HCM and passing lanes could also
43   be evaluated. However, the conclusions were based on simulations.
44   Moreover, the characteristics of the passing zone itself may influence on its effectiveness to
45   allow passing maneuvers. From one of the only field studies on passing activities (*1*), it can be
46   concluded that the longer the passing zone, the higher passes per unit length (passes/h/km).
47   Furthermore, passing maneuvers are limited and typically performed using the opposing lane when
48   sight distance and gaps in the opposing traffic stream permit. Therefore, passing frequencies may be

1   optimized on the same passing zone at some traffic volume, from which it will decrease the number of
2   gaps in the opposing traffic stream and so the passing opportunities. Romana (*1*) found that passing
3   was effective as relief and improvement of level of service for balanced flows around 500 to 800
4   veh/h. However, the data sets were obtained from three highways with different lengths and traffic
5   flows.
6   The present research deepens on the analysis of passing zones effectiveness considering the
7   number of passes and the number of passes per following vehicle, depending on the passing zone
8   length and traffic volume.
9
10   **OBJECTIVES AND HYPOTHESES**
11
12   The aim of this research is to analyze the operational effectiveness of passing zones depending on the
13   passing zone length and the traffic volume. Data were collected on four passing zones of one rural
14   highway in Spain, with two-way traffic volumes ranging from 100 vh/h to 900 vh/h and lengths
15   between 265 and 1270 m. So, the influence of traffic flow on passing rates was calculated on the same
16   passing zones with different lengths. The effectiveness of passing zones was obtained from passing
17   frequency, as the number of passing maneuvers (passes) per 15-minute period, and from passing rate,
18   as the number of passing maneuvers per 15-minute period and following vehicle. The results were
19   validated with additional data from another twelve passing zones with different lengths and traffic
20   volumes.
21
22   Based on the literature, the following hypotheses have been established:
23
24   -   Passing frequency and passing rate would increase as the length of the passing zone increases.
25   -   Passing frequency and passing rate would increase as the two-way traffic flow increases until
26   a maximum value, from which they would decrease as the gap sizes on the opposing traffic
27   stream decrease.
28
29   **METHODOLOGY**
30
31   The methodology was conducted on three stages: field study; data reduction; and analysis of the
32   results.
33
34   **Field study**
35   Data were collected in four passing zones on the N-225 highway in the province of Valencia, Spain.
36   The total length of the highway segment is 15 km and it connects two major intercity routes and
37   serves to daily commuter routes. Therefore, it can be classified as Class I two-lane highway. Design
38   speed, as well as posted speed limit, is 100 km/h. Cross section was 3.5 m lane width and 1.5 m
39   shoulder width. Annual average daily traffic was 5,577 veh/day in 2010.
40   The four passing zones, two on each travel direction, were located between stations 4+000
41   and 6+000 in a tangent; with a no-passing zone between them caused by a vertical crest curve (Figure
42   1). Their lengths were 265 and 1,270 m on the East bound; and 1,050 and 507 m on the West bound
43   (Table 1).
44   A mobile traffic laboratory (*19*) was placed between the four passing zones next to the
45   highway. It was equipped with six digital video cameras installed on the top of an elevator platform.
46   Zoom and camera focus were adjusted on site using their wireless network to collect video images of
47   the four passing zones simultaneously. Uniform quality on each zone was obtained. Videos were
48   recorded a working day between 2 pm and 9 pm. Two-ways traffic volumes ranged from 120 to 390

1   vh/h. So, different traffic flows and traffic proportion could be analyzed on the same scenarios.
2   However, high-traffic volumes were not captured. Consequently, two additional data collection were
3   carried out during two hours one Friday afternoon, with traffic volumes between 360 and 560 vh/h;
4   and another two hours one Sunday afternoon with traffic volumes between 560 and 900 vh/h. The
5   additional data were collected using two coordinated video cameras. One was located at the beginning
6   of the longest passing zones and the other camera recorded the whole shortest passing zones. They
7   were not perceived by drivers (Figure 1).
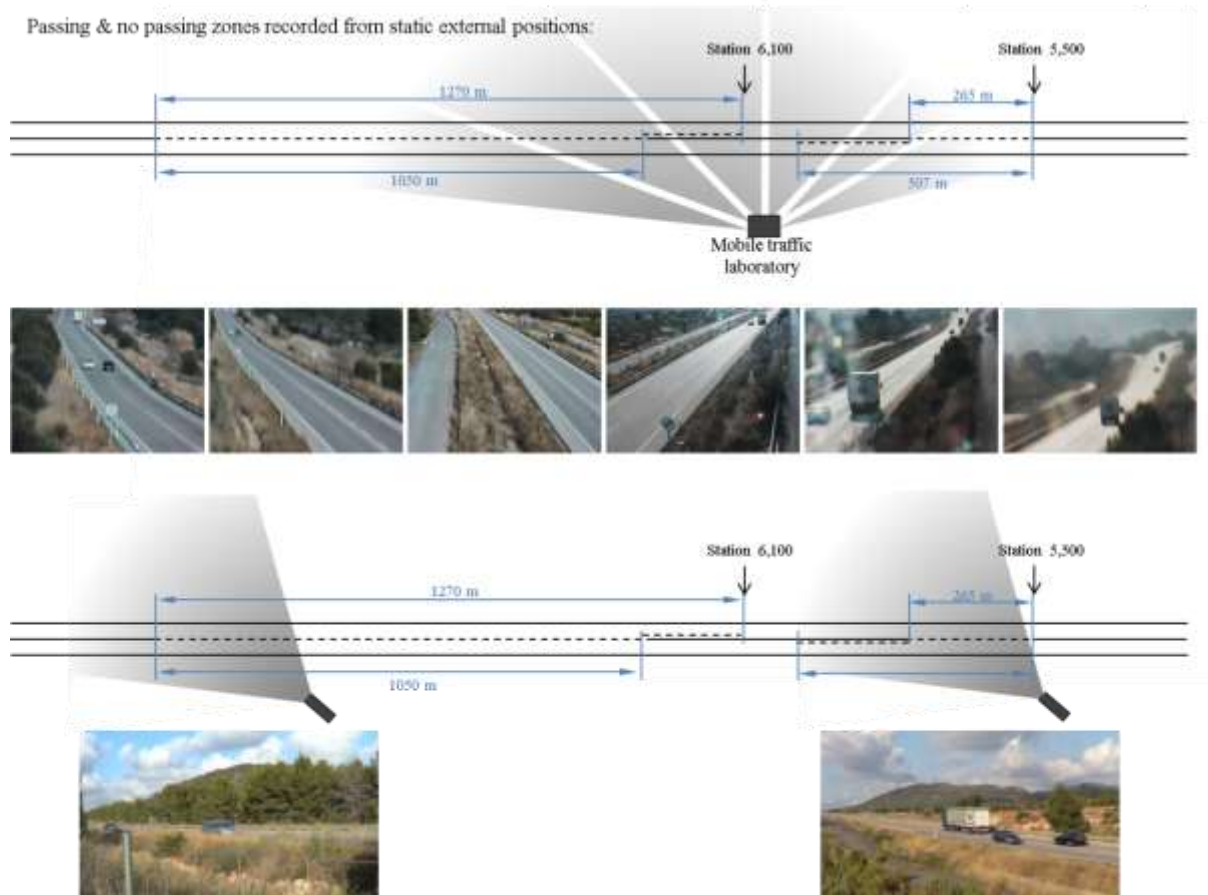
8
9   **FIGURE 1 Field study design.**

10

11 **TABLE 1 Calibration passing zones characteristics**

ID	Highway	Station (m)	Bound	Passing zone length (m)	Two-way traffic volume (veh/h)	Number of passes	Duration (h)
1	N-225	5,500	1	265	120 - 900	148	13:00
2			2	507		279	
3		6,100	1	1270		680	
4			2	1050		542	
TOTAL						1,649	52:00

12

13   In order to validate the conclusions from one highway segment, twelve more passing zones
14 were analyzed. The mobile traffic laboratory was also parked next to the passing zone. Length and
15 traffic flows of the passing zones, as well as video duration and number of passes, are summarized in
16 Table 2.

17
18
19

1   **TABLE 2 Validation passing zones characteristics**

ID	Highway	Station (m)	Bound	Passing zone length (m)	Two-way traffic volume (veh/h)	Number of passes	Duration (h)
1	CV-50	84,500	1	600	215 - 365	52	4:00
2			2	850		43	
3		77,500	1	990	175 - 420	15	2:50
4			2	755		10	
5	CV-37	14,000	1	550	180 - 375	25	3:00
6			2	560		31	
7	CV-35	76,000	1	540	100 - 150	5	5:55
8			2	522		11	
9		44,500	1	1130	180 - 305	58	4:05
10			2	1265		48	
11	CV-25	5,000	1	1000	310 – 1,100	17	3:20
12			2	1000		62	
TOTAL						**377**	**46:20**

2
3   Data were collected with dry pavement conditions and good weather, during working days. The
4   mobile traffic laboratory was proven not to influence passing maneuvers (*19*).
5
6   **Data reduction**
7   Video data was used to characterize passing frequency and passing rate. Traffic volumes, as well as
8   following vehicles (FV) were also obtained. Moreover, accepted and rejected gaps, passing times and
9   time-to-collision (TTC) were calculated for each passing maneuver for another research.
10   The counting period was 5 minutes and the results were aggregated in 15 minutes as the sum
11   of three overlapping consecutive 5-minute period in order to skip the error of peak 15-minute period
12   overlapped on two 15-minute counting periods (*17*).Then, equivalent hourly data were calculated
13   based on the 15-minute data. Consequently, 456 15-minute periods were considered on the N-225,
14   114 15-minute periods per passing zone. A total of 553 15-minute periods were analyzed considering
15   the additional passing zones. The 15-minute period was chosen over hourly period times in order to
16   better represent passing maneuvers, as peak traffic volumes and traffic proportion are smoothed on
17   hourly periods. Besides, the capacities and service flow rates of the HCM are based on 15-minute
18   periods.
19   Three-second headway was used to determine following vehicles: all the vehicles that had
20   headway lower than 3 seconds with the preceding car were considered following vehicles. Percentage
21   of following vehicles on the 15-minute period was calculated as the number of following vehicles
22   divided by the number of vehicles on that traffic direction.
23   Passing maneuvers were obtained from the videos. As complete passing zones were recorded
24   with the mobile traffic laboratory, passes were counted viewing the video. The shortest zones on the
25   high-volume data collection were also recorded completely, so passing maneuvers were counted from
26   the video without further data reduction. Passing maneuvers on the longest passing zones on high-
27   volume data collection were obtained comparing the order of the vehicles at the beginning and the end
28   of the passing zone. Whenever a change in sequence of vehicles was observed between the two
29   videos, it was concluded that a passing maneuver had occurred on the passing zone. A total of 1,649
30   passes were observed on the calibration scenarios on the 53 hours of videos. Passing maneuvers from
31   the twelve validation scenarios were 377 on 46 hours.
32   Finally, passing rates were calculated dividing the number of passing maneuvers by the
33   following vehicles at each 15-minute period. Consequently, a passing rate of 0.5 passes/following veh
34   means that 50% of the vehicles following a leader inside a platoon performed a passing maneuver.
35

1   **ANALYSIS OF THE RESULTS**
2
3   One of the common mistakes on the statistical analysis of the results is to model the phenomenon
4   without checking the assumptions of the statistical tests. For example, linear regression cannot be
5   applied to count data, such as number of following vehicles, because they are not normally
6   distributed. On the analysis, the most appropriated statistical test for each variable was considered.
7   The following variables were analyzed: following vehicles (FV); percentage of following vehicles
8   (%FV); passing frequency (PF); and, passing rates (PR). The results are presented on the following
9   sections.
10
11 **Traffic characteristics**
12 Following vehicles and percentage of following vehicles were analyzed to characterize the traffic flow
13 on the beginning of the passing zones.
14   As following vehicles are nonnegative integer values, usual statistical tests based on the
15 assumption of a normal distribution, such as linear regression, cannot be applied. Usually, count data
16 are modeled with a Poisson regression model. The Poisson model assumptions of non-truncated data,
17 equality of mean and variance and non-preponderance of zeros were met. Consequently, the Poisson
18 regression model was applied. The results of the Poisson regression model indicated that the one-way
19 volume (veh/h) explained an 87% of the following vehicles variance ($\alpha = 5\%$, R_p-Squared = 86.8 %),
20 as Equation 1 shows. As observed, the number of following vehicles increases as the one-way traffic
21 volume increases. The statistics are summarized on Table 3.
22
23 $$FV = \exp(1.35206 + 0.0277104 * V_p)$$ (1)
24
25   Where: FV is the number of following vehicles in a 15-minute period (veh/h) and Vp is the
26 one-way traffic volume for a 15-minute period (veh/h).
27
28 **TABLE 3 Poisson regression analysis for following vehicles**

Poisson Regression Analysis				Deviance Analysis			
Parameter	**Estimate**	**Standard error**	**Estimated rate ratio**	**Source**	**Deviance**	**DF**	**P-Value**
CONSTANT	1.35206	0.0278301		Model	4624,99	1	0.0000
One way traffic volume	0.027710	0.0003904	1.0281	Residue	697,759	454	0.0000
				Total (Corr.)	5322.75	455	
DF= degrees of freedom; corr. = correlation; R^2 = 86.9 %; R^2 (adjusted) = 86.8 %							

29
30   On the other hand, the percentage of following vehicle was a continuous data set. Probability
31 plot, skewness and kurtosis were carried out to verify if data were distributed as a normal distribution.
32 The results indicated that the variable was normally distributed. As the other assumptions of linear
33 regression analysis were fulfilled, a linear regression model (Table 4) was elaborated for the
34 percentage of following vehicles ($\alpha = 5\%$, R-Squared = 64.6 %). It could be observed that the
35 percentage of following vehicles increased as the one-way traffic volume increases (Equation 2).
36
37 $$\% FV = 0.119165 + 0.00461303 * V_p \% FV = 0.119165 + 0.00115326 * V_p$$ (2)

1

2   Where: % FV is the percentage of following vehicles in a 15-minute period (veh/veh) and Vp

3   is the one-way traffic volume for a 15-minute period (veh/h).

4

5   **TABLE 4 Multiple regression analysis for percentage of following vehicles**

Multiple Regression Analysis					Variance Analysis					
Parameter	Estimate	Standard error	t-statistic	P-value	Source	Squares Sum	DF	mean square	F-Ratio	P-Value
CONSTANT	0.119165	0.00825645	14.433	0.0000	Model	5.27343	1	5.27343	831.83	0.0000
One way traffic volume	0.004613	0.00015994	28.8414	0.0000	Residue	2.87816	454	0.00633		
					Total (Corr.)	8.15159	455			
DF= degrees of freedom; corr. = correlation; R^2 = 64.69 %; R^2 (adjusted) = 64.61 %; standard error of estimate = 0.0796; Average absolute error = 0.0633										

6

7   **Passing frequency**

8   Passing frequency was studied using the absolute number of passes in a 15-minute period in order to

9   compare with other studies. In order to analyze whether the passing frequency among passing zones

10 and traffic volume was equal, parametric and nonparametric tests could be developed. Parametric tests

11 are vastly used and preferred because they are more powerful and are more likely to lead correctly to

12 rejection of a false null hypothesis. However, the variables should be approximate normal. As passing

13 frequencies in a 15-minute period failed to be distributed as a normal distribution, the nonparametric

14 techniques should be considered.

15   The Kruskal-Wallis test is the nonparametric equivalent to the independent samples single-

16 factor analysis of variance. The test is sensitive to the differences in location (mean or median)

17 between the populations and it is identical to the Mann-Whitney U test for comparing more than two

18 populations. The null hypothesis is that all populations have the same locations (median or mean).

19 Passing frequencies were tested to have the same location considering the passing zone length. The

20 results of the Kruskal-Wallis test (sample $_{passing\ zone}$ = 114; D-statistic = 105.681; p-value $_{D\text{-statistic}}$

21 =0.0000) indicated statistical differences among values of passing frequencies at a 95% level of

22 confidence. The same test was performed based on the traffic volume on the four passing zones. The

23 results of the Kruskal-Wallis test (sample $_{traffic\ volume\ intervals}$ = [10, 166]; D-statistic = 130.386; p-value $_{D\text{-}}$

24 $_{statistic}$ =0.0000) also indicated that the different traffic volume produced statistically significant

25 differences on the passing frequency.

26   As the passing frequency had statistically significant differences depending on the passing

27 zone length and the two-way traffic volume, a regression analysis was carried out. Given that the

28 passes are nonnegative integer values, the variable was modeled as a Poisson regression model. The

29 assumptions of the model (non-truncated data, same mean and variance, and non-preponderance of

30 zeros) were fulfilled. The best fit of Poisson regression model (Table 5) is shown in Equation 3 (α =

31 5%, R_p-Squared = 62.1 %).

32

33 $$PF = \exp\left(-4.57904 - 0.00125*V_p^2 - 0.0000013*L^2 + 2.75645*P + 0.04093*V_p + 0.003455*L\right) \quad (3)$$

34

1   Where: PF is the passing frequency on the travel direction in a 15-minute period (passes/h);
2   Vp is the two-way traffic volume for a 15-minute period (veh/h); L is the length of the passing zone
3   (m); and P is the traffic proportion on the travel direction.
4
5   **TABLE 5 Poisson regression analysis for passing frequency**

Poisson Regression Analysis				Deviance Analysis			
Parameter	**Estimate**	**Standard error**	**Estimated rate ratio**	**Source**	**Deviance**	**DF**	**P-Value**
CONSTANT	-4.57904	0.327803		Model	1052.11	5	0.0000
Two-way traffic volume^2	-0.000125	0.000011536	0.999874	Residue	641.783	450	0.0000
Length^2	-0.0000013	3.01931E-7	0.999999	Total (Corr.)	1693.89	455	
Traffic proportion	2.75645	0.37668	15.7438				
Two-way traffic volume	0.04093	0.00284811	1.04178				
Length	0.003455	0.000491578	1.00346				
DF= degrees of freedom; corr. = correlation; $R^2 = 62.1 \%$; R^2 (adjusted) = 61.4 %							

6
7   Figures 2 and 3 were generated applying Equation 3 varying: traffic volume and passing zone
8   length. Traffic proportion was assumed 50/50 (P = 0.5). Two-way traffic volume in vehicles per hour
9   was represented to facilitate the analysis and it was calculated multiplying by 4 the traffic volume for
10   a 15-minute period. Moreover, passing frequencies from other 12 passing zones were plotted in two
11   series considering their length (lower than 750 m and higher than 750 m). As traffic flow influenced
12   the passing maneuver, three traffic flow levels were separated for each passing zone. The levels had
13   similar sample and number of passing maneuvers. Therefore, the behavior was more homogeneous
14   within the same level. Average traffic flow and average number of passes were calculated and plotted.
15   As seen in Figure 2, the longer the passing zone, the higher passing frequency in a 15-minute
16   period. This influence depends on the traffic volume, as dispersion varies. On the other hand, there is
17   an optimum traffic volume that maximizes the number of passes. The optimum two-way traffic
18   volume is between 600 and 700 vh/h for all the passing zones. From that value, the number of passes
19   decreases as the gaps on the opposing stream are shorter.
20
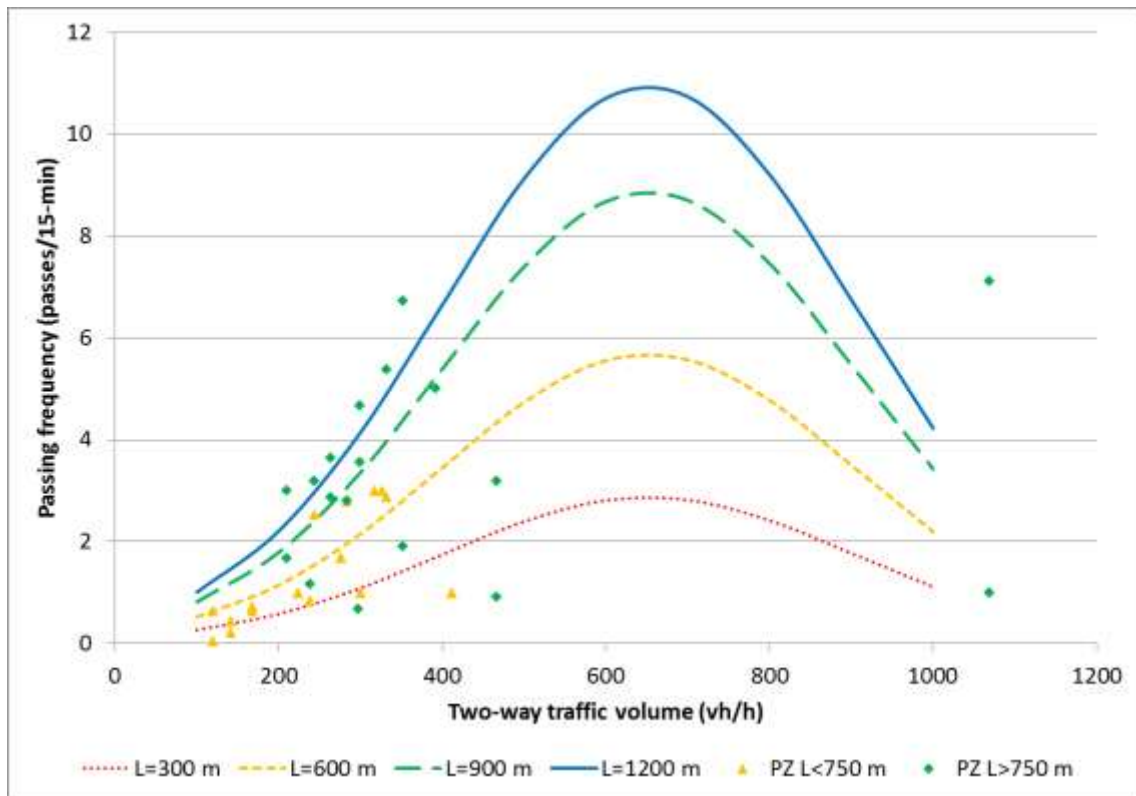
1
2 **FIGURE 2 Traffic volume influence on passing frequency for balanced flows.**
3

4   The model was validated with data from other twelve passing zones that were not introduced
5   on the model. A good adjustment of the data to the model was found. However, passing frequencies
6   of the CV-25 passing zones were different than the predicted because the traffic proportion in those
7   highways was highly directional (between 90/10 and 70/30) and much higher than on the four passing
8   zones of the model. Equation 3 was applied with CV-25 traffic proportion and the prediction was
9   much more accurate.
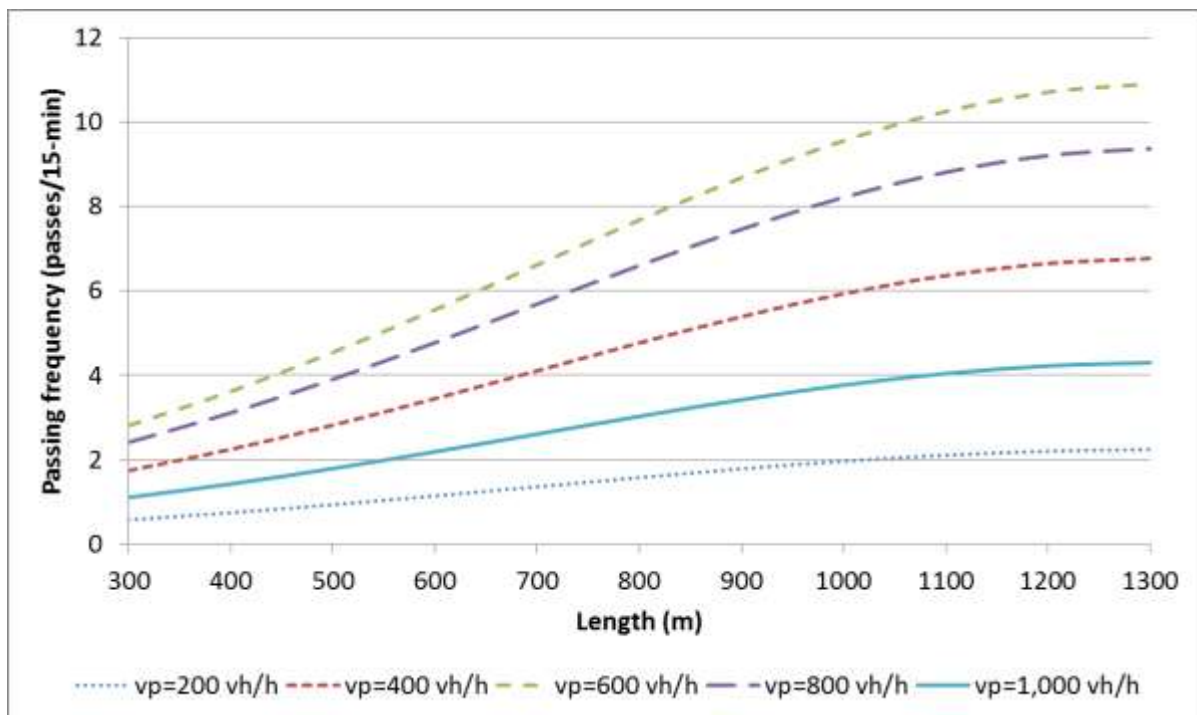
10
11 **FIGURE 3 Passing zone length influence on passing frequency for balanced flows.**

1
2   The effect of passing zone length on passing frequency is represented on Figure 3: the longer
3   passing zone, the higher passing frequency. The increase rate of passing frequency is almost linear
4   until 1,100 m. The increase rate also depended on traffic volume: the most favorable traffic volume
5   was 600 veh/h, because increasing 200 m the passing zone would increase 1.9 passes/15 min the
6   passing frequency. The same increasing of 200 m would generate an increase of 0.8, 1.2, 1.6 and 0.4
7   passes/15 min with traffic volumes of 200, 400, 800 and 1,000 veh/h, respectively. From 1,100 m
8   long, the increase rate is stabilized. Consequently, not the double of passing zone length may result in
9   the double of passes, given traffic volume and traffic proportion. This could be explained because all
10   drivers willing to pass would have already performed the maneuver. Thereafter, the length of the
11   passing zones along the highway may be considered instead of the proportion of highway without
12   passing zones because the increase on passing frequency due to passing zone length has lower
13   effectiveness from passing zones longer than 1,100 m.
14
15   **Passing rate**
16   Effectiveness of passing zones was studied depending on the absolute number of passes. However,
17   this variable could not fully represent the phenomenon because not every vehicle in one passing zone
18   is willing to pass. Consequently, passing rate was defined. The passing rate (PR) is the ratio between
19   the number of passes in a 15-minute period and the percentage of following vehicles in that same
20   period. This concept is equivalent to the overtaking ratio defined by Morrall and Werner (*18*).
21   Passing rates were tested to be distributed as a normal distribution. The normality plot, as well
22   as the kurtosis and skewness indicated that passing rates were not normally distributed. Consequently,
23   the variable was transformed to the square root of the passing rate ($PR^{0.5}$), which was normally
24   distributed and usual statistic tests could be applied.
25   An ANOVA test was carried out to identify the influence variables on passing rate. The
26   assumptions of the ANOVA test were fulfilled. The results indicated that the average values were
27   statistically different among passing zones (F-statistic = 45.74; dg = 455; p-value $_{F-statistic}$ = 0.0000; α =
28   5%).
29   As the assumptions of the multiple regression analysis were fulfilled, a forward-selection
30   multiple regression analysis was performed to determine the variables that influenced on passing
31   rates. The best fit regression model (Table 6) is presented in Equation 4 (α = 5%, r^2_{adj} = 40.5 %). The
32   adjusted R-Square was lower than the passing frequency model. It could be possible that not all
33   vehicles inside a platoon are willing to pass. Consequently, passing rates have more variability than
34   passing frequencies.
35
36      $$PR^{0.5} = 0.638004 + 0.000228171*L - 0.297747*P - 0.00174589*v_p \qquad (4)$$
37
38   Where: PR is the passing rate on the travel direction in a 15-minute period (passes/following
39   vehicle/15 min); Vp is the two-way traffic volume for a 15-minute period (veh/15 min); L is the
40   length of the passing zone (m); and P is the traffic proportion on the travel direction.
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1

2 **TABLE 6 Multiple regression analysis for passing rate**

Multiple Regression Analysis					Variance Analysis					
Parameter	Estimate	Standard error	t-statistic	P-value	Source	Squares Sum	DF	mean square	F-Ratio	P-Value
CONSTANT	0.638004	0.0653792	9.75852	0.0000	Model	5.94418	3	1.98139	86.26	0.0000
Length	0.000228	0.00001956	11.6619	0.0000	Residue	8.54465	372	0.02296		
Two-way traffic volume	-0.001745	0.00017091	-10.2149	0.0000	Total (Corr.)	14.4888	375			
Traffic proportion	-0.297747	0.113547	-2.62224	0.0091						
DF= degrees of freedom; corr. = correlation; R^2 = 41.0 %; R^2 (adjusted) = 40.5 %; standard error of estimate = 0.1515; Average absolute error = 0.1160										

3

4 As seen, the longer the passing zone, the higher passing rate. On the other hand, favorable
5 traffic proportion resulted in higher passing rates. However, traffic volume was not statistically
6 significant. It could be explained as the number of following vehicles is correlated with the traffic
7 volume.

8 The influence of traffic volume and passing zone length on passing rate is shown in Figure 4.
9 It was generated applying Equation 4 varying traffic volume and passing zone length. Similar to
10 Figures 2 and 3, traffic proportion was assumed 50/50 (P=0.5) and two-way traffic volume in vehicles
11 per hour was represented to facilitate the analysis. It was calculated multiplying by 4 the traffic
12 volume for a 15-minute period. Passing rates from the other 12 passing zones were also plotted with
13 the same criteria.

14
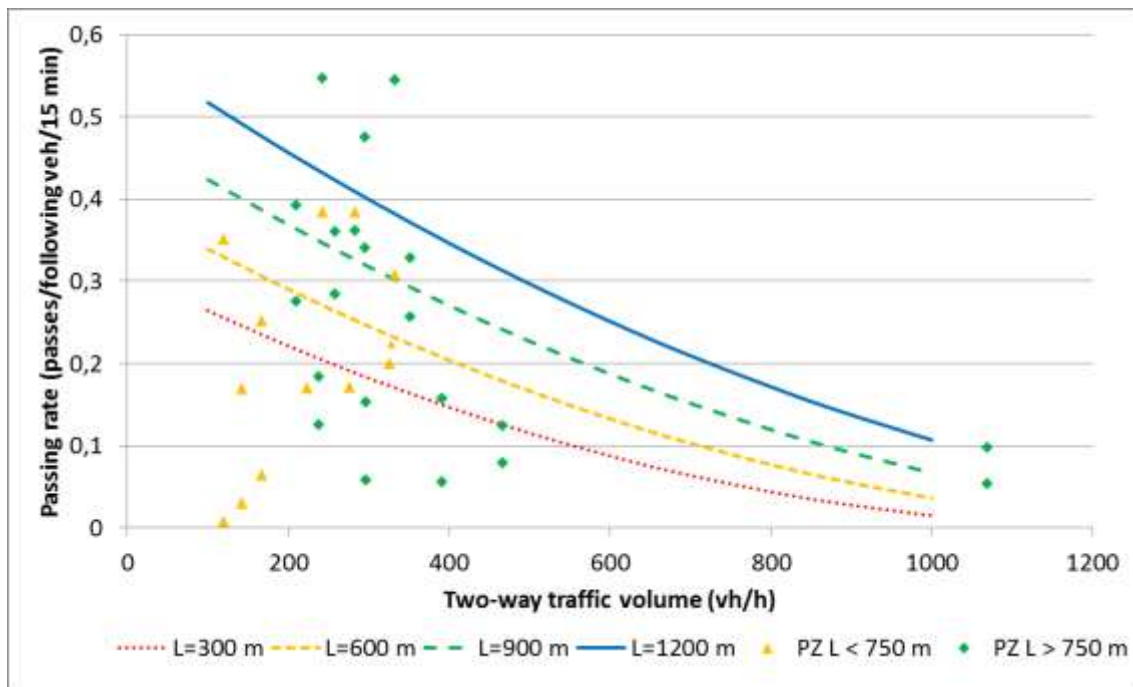
15
16 **FIGURE 4 Traffic volume influence on passing rate for balanced flows.**

17

18 The number of completed passes per following vehicle increases as the traffic volume
19 decreases and the passing zone length increases. With short passing zones, only 26% of following

1 vehicles can perform the maneuver even though traffic volume is quite low (200 veh/h) and passing
2 gaps are available. For the same traffic volume, passing zones of 1,200 m increase the percentage of
3 following vehicles that pass to 52%. The results are consistent for all traffic volumes. However, the
4 decrease rate is higher on longer passing zones as increasing 200 veh/h the two-way traffic flow
5 would reduce the percentage of following drivers that pass in 10%, 8%, 8% and 6% for passing zones
6 length of 1,200, 900, 600 and 300 m, respectively. On the other hand, an optimum traffic volume that
7 maximizes passing rate was not found because even though the number of passes was higher with
8 traffic volumes between 600 and 700 veh/h, the following vehicles were also higher. Consequently,
9 the percentage of following vehicles that passed always decreases with traffic volume.
10   Figure 4 could be used twofold. The first option is to calculate the passing zone length needed
11 to provide a certain passing rate given the traffic volume of the highway. The second option is to
12 evaluate until which traffic volume of the highway a certain passing rate could be guaranteed given
13 the passing zone length. So, the model could be used to determine the minimum passing zone length
14 or maximum traffic volume that provides a determinate passing rate.
15   Adjustment of validation data to the model was lower on passing rates than on passing
16 frequency due to their higher dispersion. However, it can be observed that longer passing zones
17 presented higher passing rates. Consequently, passing rate variability may be too high to consider this
18 variable even though the better representation of the phenomenon.
19
20 **DISCUSSION**
21
22 The Highway Capacity Manual (*3*) includes passing zones effect on two-lane highways traffic
23 operation on both ATS (average travel speed) and PTSF (percentage time spent following). ATS is
24 affected by the adjustment for percentage of no-passing zones: ATS is reduced is the percentage of
25 no-passing zones increases. Given a highway segment length, more passing zone length along the
26 highway would lead to higher ATS. Consequently, it assumes that the improvement on traffic
27 operation of passing zones is equal regardless their length: one passing zone of 1,500 m would have
28 the same effects on traffic operation than two passing zones of 750 m. However, the developed model
29 indicated that even though passing frequency increases as the length of the passing zone increases, the
30 increase rate is much lower from 1,100 m passing zone length. Consequently, two passing zones of
31 750 m would produce more passes and ATS would be higher than on a single passing zone of 1,500
32 m. Thereafter, the percentage of no-passing zones would not reliably represent effectiveness of
33 passing zones. Effectiveness of every single passing zone should be considered instead.
34   Furthermore, the adjustment also depends on the flow rate for peak 15-min period. Given a
35 percentage of no-passing zones, reduction in ATS is maximum for two-way demand flow (vp) of 400
36 veh/h, and its influence is stabilized for vp higher than 1,800 veh/h or more. The proposed model
37 indicates that passing frequency is optimized for traffic volumes between 600 and 700 veh/h.
38 Consequently, reduction in ATS should be minimized on that range. Moreover, if traffic volume was
39 higher than 800 veh/h passing frequency was highly reduced. So, the adjustment factor should be
40 reduced for traffic flows of 600 and 800 veh/h and then increased for higher traffic flows.
41   On the other hand, PTSF is adjusted by the combined effect of the directional distribution of
42 traffic and of the percentage of no-passing zones. The adjustment depends on percentage of no-
43 passing zones, two-way flow rate and traffic proportion. An increase on no-passing zone percentage
44 would result in higher PTSF and worse level of service. Similarly to the previous discussion,
45 effectiveness of every passing zone should be considered instead the percentage of no-passing zones.
46 Besides, increase in PTSF is maximum for two-way flow rate of 400 veh/h on balanced flows.
47 Nevertheless, the obtained model does not represent the same behavior. Thereafter, the adjustment

1   factor should be reduced for traffic flows of 600 and 800 veh/h and then increased for higher traffic
2   flows. Traffic proportion should also be considered. However, its effect is lower than other variables.
3   Conversely, the passing rate model was compared with the overtaking ratios proposed by
4   Morrall and Werner (*18*). Both parameters decreased with two-way traffic volume. However, their
5   maximum expected passing rate was 85%, compared to the 52% of the proposed model. The main
6   reason for this difference is the passing behavior. Morrall and Werner used a traffic simulation model
7   where drivers will to pass if their desired speed was lower than the impeding vehicle. However, some
8   drivers adapt their speed to the previous vehicle and accept that delay on their trip: these drivers
9   would not perform a passing maneuver. Consequently, the number of passes with low traffic volume
10   decreases, and the maximum passing rate is lower. Besides, the effect of two-way traffic volume was
11   higher on their simulations than on the model, as the expected passing rate decreased from 85 to 10 %
12   at a traffic volume of 800 veh/h. Furthermore, the minimum passing rate was stabilized at 2 %. The
13   higher decrease rate is also explained because of the passing behavior on the traffic simulation model.
14   However, Morrall and Werner presented the percentage of no-passing zones instead of single passing
15   zones. So, their values cannot be directly compared with the model.
16   Finally, the results were compared with Romana's study (*1*). Overall passing rates were
17   presented for a whole highway segment including no-passing zones instead of single passing zones.
18   Consequently, no comparison was possible without further data. However, his data showed a
19   maximum passing frequency for a balanced two-way traffic flow between 500 and 800 veh/h. This
20   optimum value is similar to the one given on the model, which is located between 600 and 700 veh/h.
21
22   **CONCLUSIONS**
23
24   Passing maneuvers have been deeply studied in highway engineering to determine criteria to establish
25   no-passing zones, as many of the studies are focused on the maneuver itself and how is performed on
26   different conditions. However, the interaction between vehicles traveling in the same and in opposing
27   lanes affects traffic operations. Most of the studies are focused on percentage of following vehicles or
28   the adjustment of the HCM procedure to local data. However, these variables are influenced by the
29   effectiveness of passing zones and how they could reduce the number of following vehicles. In fact,
30   only a few studies on the expected number of passes on a highway considering the percentage of no-
31   passing zones have been carried out.
32   This research presented an analysis of the effectiveness of passing zones considering their
33   length and traffic volume. Four passing zones located on the same rural highway in Spain were
34   selected. They presented two-way traffic volumes between 120 and 900 veh/h; and lengths between
35   265 and 1,270 m. More than 1,600 passing maneuvers were recorded during the 53 hours of
36   observation on the scenarios.
37   Passing frequency and passing rate were selected as passing zone effectiveness measures.
38   Passing frequency is defined as the number of passes per 15-minute observation period. The count
39   data were modeled following a Poisson regression model. The results indicated that the longer the
40   passing zone, the higher number of passes in the period. However, the improvement on passing
41   frequency is more stable from passing zone lengths longer than 1,100 m. From that length, the
42   effectiveness of the passing zones decreases because the drivers willing to pass would perform the
43   maneuver with shorter passing zones and the increase would only affect to very conservative drivers
44   that need much longer gaps on the opposing stream. On the other hand, balanced flows with two-way
45   traffic volumes between 600 and 700 veh/h optimized the number of passes. This result was
46   consistent for all lengths and suggested that passing is more effective for that traffic conditions.
47   Even though passing frequency quantifies the number of passes in a passing zone, this
48   measure is not enough to fully represent the phenomenon: passing maneuvers need a faster vehicle

impeded by a lower vehicle; so, not every vehicle that enters a passing zone is willing to pass. Consequently, passing rate was defined as the number of passes per following vehicle per 15-minute observation period. Passing rate decreased as traffic volume increased, for all passing zones. So, the increase in the passing frequency with the traffic volume is lower than the increase of following vehicles. Besides, the model predicted that the maximum percentage of drivers that follow a vehicle and could perform a passing maneuver was 52 %; with two-way traffic volume of 200 veh/h and passing zone length of 1,200 m. The model could be used to determine the minimum passing zone length or maximum traffic volume that provides a determinate passing rate.

The passing frequency and passing rate models were validated with data from other twelve additional passing zones. The additional scenarios presented different traffic volumes and lengths. 377 passes were observed on the validation scenarios during more than 46 hours. The passing frequency model was accurately adjusted to the additional data while the passing rates presented the same trends but with higher dispersion. Thereafter, even though this variable better represents the phenomenon, its variability may be too high for consideration.

The results were compared with the 2010 Highway Capacity Manual analysis procedure for two-lane highways. Adjustments on average travel speed and percentage time spent following based on percentage of no-passing zones do not reliably represent effectiveness of passing zones. Effectiveness of every passing zone should be considered instead.

Finally, the paper presented a new approach to two-lane highway traffic performance based on the effectiveness of passing zones. General conclusions on passing zones effectiveness were given. Further research will be carried out to reduce more data such as vehicles' speeds. The results could be used to calibrate a traffic simulation model on two-lane highways in order to generate new highway scenarios and propose reliable thresholds on traffic operation quality.

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