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OPERATIONAL CONSIDERATIONS OF PASSING ZONES FOR TWO-LANE HIGHWAYS: SPANISH CASE STUDY

ABSTRACT

The U.S. Highway Capacity Manual (HCM 2010) methodology is used in Spain to evaluate traffic operation and quality of service. In two-lane undivided highways, the effect of limiting where drivers could pass slower vehicles, or passing restrictions, is considered through the percentage of no-passing zones. This measure does not account for how passing opportunities are distributed along the road. The objective of this research was to evaluate the effect percentage of no-passing zones and average passing zone length on a two-lane highway and, if significant, incorporate them in the analysis methodology. The TWOPAS microsimulation program was calibrated and validated to the Spanish conditions. Passing restrictions had little effect on average traffic speed (ATS), with differences lower than 6 km/h between a road segment with no passing restrictions and a road segment with a passing restriction on 100% of its length. Conversely, passing restrictions can increase the percent time spent following (PTSF) up to 30%. Increasing the passing zone length beyond 2,000 m does not improve PTSF. The new models could be used to better estimate traffic operation on Spanish two-lane highways.

KEYWORDS

traffic operation; two-lane highway; percent time spent following; average travel speed; passing restriction; passing zone;

1. INTRODUCTION

Two-lane undivided highways have a level of interaction between vehicles traveling in the same and opposite directions which results in unique operational characteristics. This is mainly because faster vehicles wishing to travel at their desired speed must use the oncoming lane to pass slower vehicles (where a passing lane is not present). To ensure road safety, design guidelines allow passing only in those zones where available sight distance is long enough to perform passing maneuvers and where oncoming traffic permits [1,2].

Passing behavior has been largely studied with different purposes. Most of the studies are centered on determining adequate passing sight distance criteria [3–5] and quantifying the number of passing maneuvers at isolated passing zones [6–11]. Rare are studies that explicitly link passing zone characteristics to traffic operations.

Evaluation of quality of service on two-lane highways

In order to analyze traffic efficiency, Spanish standards [2] rely on the procedures of the U.S. Highway Capacity Manual (HCM) [12]. For two-lane highways, the level of service is based on one or more of three performance measures, depending on highway classification

[2, 12]: average travel speed (*ATS*), percent time spent following (*PTSF*), and percent free flow speed (PFFS). *PTSF* is defined as the average percent of total travel time that vehicles must travel in platoons behind slower vehicles due to the inability to pass. *PTSF* is difficult to measure in the field, and the HCM recommends to use percent followers as the surrogate measure for field estimation of *PTSF*. The HCM procedure starts with estimating traffic performance for the base scenario (i.e., passing is allowed along the entire length of the segment), adjusting traffic demands to account for heavy vehicles and grade impacts. Then, passing restriction effects are considered through adjustment factors to the performance measures of specific segment. *ATS* has a linear relationship with directional and opposing traffic flow, while *PTSF* varies exponentially with directional traffic flow. Passing restriction adjustments depend on the percentage of no-passing zones and directional split. This ratio is complementary to the percentage of length on which vehicles can pass. However, this measure does not account for how passing opportunities are distributed along the road. Consequently, two highways with equal percentage of no-passing zones will produce the same operational results.

The adjustments to account for passing restrictions are based in large part on simulation results from the microsimulation program TWOPAS [13, 14]. TWOPAS was originally developed by the Midwest Research Institute (between 1971 and 1974), and had occasional updates through the late 1990s. TWOPAS is currently packaged with the Traffic Analysis Module of the Interactive Highway Safety Design Model (IHSDM) from the Federal Highway Administration (FHWA). To develop the HCM procedure, field data collected in the 1990s was used to calibrate TWOPAS results on *ATS* and *PTSF*, although passing behavior was not updated [13]. Moreover, no indications on the precision of the adjustment or how passing zones were distributed were given [14].

Local adaptations of the HCM analysis procedure for two-lane highways were performed in Finland [15, 16, 17], Brazil [18, 19], Argentina [20], India [21], and Spain [22], while Germany has its own analysis procedure [23, 24]. The most commonly used performance measures (in all countries' two-lane highway analysis procedures) are *ATS* and *PTSF*, with notable exceptions being that Germany uses density; Finland does not consider *PTSF*, and the *ATS* of interest is just for passenger cars; and India includes the number of followers as a proportion of capacity. The effect of passing restrictions is considered through the percentage of no-passing zones in the U.S., Finland, Brazil, Argentina, and Spain. In India, passing restrictions are not considered because there are no delimited passing zones [21]. In Germany, passing restrictions were considered on the previous analysis procedure

[24]. However, they were removed on the current version [23] because its impact on speed was marginal compared to differences on roadway alignment [25]. As a result, actual characteristics and distribution of passing zones (number and length) are not used in any analysis procedure.

Effects of passing restrictions on traffic performance

Passing zone length may affect traffic operations. According to experimental data collected by Harwood et al. [4, 26] to determine U.S. passing sight distance criteria, short passing zones with lengths of 120 to 240 m contribute little to the traffic operational efficiency of two-lane roads, with observed 0.77 passes per hour compared to 2.95 passes per hour at longer passing zones (passing zone length from 300 to 1,650 m). Additionally, Harwood et al. used the simulation program TWOPAS to evaluate the contribution of short passing zones. The results indicated that short passing zones had little effect on *ATS* or *PTSF*, compared to the total passing restriction [4].

Similar results on isolated passing zones were obtained in Spain [10] and Uganda [11]. Experimental data from external observations showed that increasing the passing zone length over 1,100 m did not improve the passing rate much [10]. Simulations in Aimsun with the same scenarios as Harwood et al. [4] indicated that passing zones shorter than 250 m add very little to operational efficiency compared to 100% no-passing zones, in terms of *ATS* and *PTSF* improvement [27].

Research statement

The HCM analysis procedure accounts for the effect of passing restrictions through the percentage of no-passing zones. Consequently, two highways with the same length, but the first with one passing zone of 2,500 m and the second with ten passing zones of 250 m, will have the same results, which is quite unrealistic, as previous studies concluded that very short passing zones contribute little to traffic operations [4, 10, 11]. To overcome this shortcoming, we added one second parameter: average passing zone length. Moreover, passing behavior field data used for the development of the HCM analysis methodology was from the 1970s [13, 14], and it is not clear what changes in motorist passing behavior may have taken place in the subsequent years.

Therefore, there is a need to document current passing behavior and relate it to traffic performance, in order to determine when passing restrictions would limit traffic efficiency. Unfortunately, field measurements can be expensive, and, even more importantly, they rarely provide sufficient repeatability for the full range of traffic demands and passing restrictions. At this point, traffic microsimulation must be considered.

The objective of this study was to analyze the effect of passing restrictions on two-lane highway traffic performance. Based on the results, criteria to analyze traffic operations on two-lane highways are proposed.

Basic hypotheses

Based on the literature review, the following hypotheses have been established:

- Distribution of passing restrictions will influence traffic operations. Given the same percentage of no-passing zones, configurations with few long passing zones will perform better than configurations with many short passing zones.
- Operational improvement due to passing will be minimized at high traffic volumes or at unbalanced traffic flows. Under those conditions, the number of passes would decrease as the gap sizes on the opposing traffic stream decrease.
- The effect of passing restrictions will be higher on *PTSF* than *ATS*. The inability to pass directly affects *PTSF*, as this variable starts being computed when vehicles are not traveling at their desired speed. Nevertheless, the inability to pass reduces speed compared to the desired speed. Given that speed dispersion is not extremely high, the overall effect would be low.

2. METHODOLOGY

This study is based on microsimulation results from the TWOPAS program. TWOPAS was selected because it was previously used to develop the HCM analysis procedure, and it was the only program available at the time of the research that was calibrated using field data.

The methodology is as follows:

- 1) Documenting current passing behavior on Spanish two-lane highways.
- 2) Calibrating and validating TWOPAS by using a genetic algorithm. Passing behavior is also calibrated, as passing rate was included within the fitness function.
- 3) Generating and simulating multiple scenarios in TWOPAS with varying directional traffic flow, directional split, heavy vehicles percentage, and passing restrictions.

- 4) Modeling traffic operations for the base conditions (i.e., no passing restrictions).
- 5) Modeling traffic operations for scenarios with passing restrictions.

Tasks 1 and 2 were carried out as a part of a previous study that feeds into this research [22]. They are summarized in the following sections.

2.1 Field data

Data was collected across four passing zones located along the two-lane highway N-225 in Spain. The characteristics of the passing zones are summarized in *Table 1*.

Video recordings were made at the beginning and end of the passing zones. The videos were individually analyzed to obtain the time stamp of each vehicle. Directional traffic volume, traffic composition, average travel time, and time headway were obtained. The HCM recommends a 3-second headway threshold for the purpose of estimating percent followers (PF) [12]. The number of passing maneuvers was calculated by comparing the vehicles' order at the beginning and end of the passing zone. Variations on the order indicated the performance of passing maneuvers. Changes in two or more positions of the same vehicle were considered as one multiple passing maneuver. A total of 52 hours of video data was collected on N-225. Data was collected during daytime hours under good weather conditions, and the pavement was in good condition.

Passing behavior on N-225 was validated with observations from 12 additional passing zones [10] (*Table 2*). Passing rate was used as a validation parameter. The results indicated that the observed passing behavior on N-225 did not differ much from other passing zones.

2.2 Calibration and validation of TWOPAS

The N-225 highway was created in TWOPAS. The posted speed equals 100 km/h, and it has 3.5 m lane width and 1.5 m shoulder width. Mean desired speed and standard deviation were estimated based on the unimpeded speed distributions, considering headways longer than 6 seconds [28]. Percentage of each vehicle type was assigned based on the observations. For passenger cars, maximum acceleration and overall

Table 1 – Characteristics of the passing zones from N-225

ID	Highway	Station coordinates	Bound	Passing zone length [m]	Two-way traffic flow [veh/h]	Number of passes	Duration [h]
1	N-225	(39.769975, -0.339681)	1	265	120 - 900	148	13:00
2			2	507		279	
3		(39.775352, -0.327514)	1	1,270		680	
4			2	1,050		542	
TOTAL for calibration and validation of TWOPAS						1,649	52:00

Table 2 – Validation of passing behavior: characteristics of the passing zones

ID	Highway	Station coordinates	Bound	Passing zone length [m]	Two-way traffic flow [veh/h]	Number of passes	Duration [h]
1	CV-50	(39.556447, -0.636202)	1	600	215 - 365	52	4:00
2			2	850		43	
3		(39.507880, -0.679913)	1	990	175 - 420	15	2:50
4			2	755		10	
5	CV-37	(39.546027, -0.584209)	1	550	180 - 375	25	3:00
6			2	560		31	
7	CV-35	(39.718898, -0.960986)	1	540	100 - 150	5	5:55
8			2	522		11	
9		(39.701843, -0.775658)	1	1,130	180 - 305	58	4:05
10			2	1,265		48	
11	CV-25	(39.665049, -0.566562)	1	1,000	310 - 1,100	17	3:20
12			2	1,000		62	
TOTAL for validation of passing behavior						377	46:20

length were adjusted for the five vehicles type (Renault Clio, Renault Megane, Ford Mondeo, Peugeot Partner, Nissan Terrano). Similarly, weight/net horsepower ratio, weight/projected frontal area ratio, and overall length were adjusted for the two trucks types (Scania P 270 4x2, Volvo FH tractor).

The goal of the calibration is to find the combination of parameters that minimizes the differences (*ATS*, *PTSF*, passing rate) between the simulation and field data. For this research, the genetic algorithm from Bessa and Setti [18, 19] was utilized.

The genetic algorithm's objective is to minimize the fitness function. This function was defined as the mean average square error between the simulated results and field data (*Equation 1*). It depended on 20 parameters (10 per direction).

$$F = \frac{1}{M} \cdot \sum_{i=1}^M \sum_{j=1}^N \sum_{k=1}^K w_k \cdot \left| \frac{V_{OBS_{ijk}} - V_{SIM_{ijk}}}{V_{SIM_{ijk}}} \right| \quad (1)$$

where:

F – fitness function;

M – number of road segments;

N – number of demand periods;

K – number of parameters. They include, per travel direction: number of passes, percent followers at the end of the segment (3 second headway criterion); average speed of passenger cars and trucks; standard deviation of speed of passenger cars and trucks; 15th percentile from speed distribution of passenger cars; 15th percentile from speed distribution of trucks; 85th percentile from speed distribution of passenger cars; 85th percentile from speed distribution of trucks;

w_k – weight of the parameter;

V_{OBS} – observed value;

V_{SIM} – simulated value.

Given that there were more speed-related variables than passing-related variables within the fitness function, assignment of equal weighting to all variables would likely produce suboptimal outcomes. Therefore, three combinations of weights were tested for the fitness function variables. The sensitivity analysis considered four generations for each combination. Ultimately, the combination that minimized the average error and individual variable error was: weighted passes 86%, percent followers 6%, and speeds 8%.

The genetic algorithm was executed for 80 generations of 40 individuals, 5 random seeds, and 30 traffic scenarios. Each simulation run was 15 minutes long, with a 15-minute warm-up period. The mean average square error was reduced from 7.9% (default values) to 3.8% (calibrated values). The 25 best calibration parameter combinations were validated with additional field data (60 traffic scenarios). The mean average square error was 4.3%, very close to the calibration error; compared to 7.9% for the default values.

Further details on the calibration can be found in [22].

2.3 Case study scenarios

The case study included a 10-km long straight segment, with percent grade equal to 0.5%. Passing restrictions varied as follows (*Figure 1*):

- Percentage of no-passing zones: 0, 50, and 100%.
- Average passing zone length for the percentage of no-passing zones equal to 50%: 250; 500; 714; 1,000; 1,250; 1,670; 2,500; and 5,000 m. The passing zones were uniformly distributed along the segment.

Traffic variables varied as follows:

- Directional split: 20/80; 30/70; 40/60; 50/50; 60/40; 70/30; 80/20.

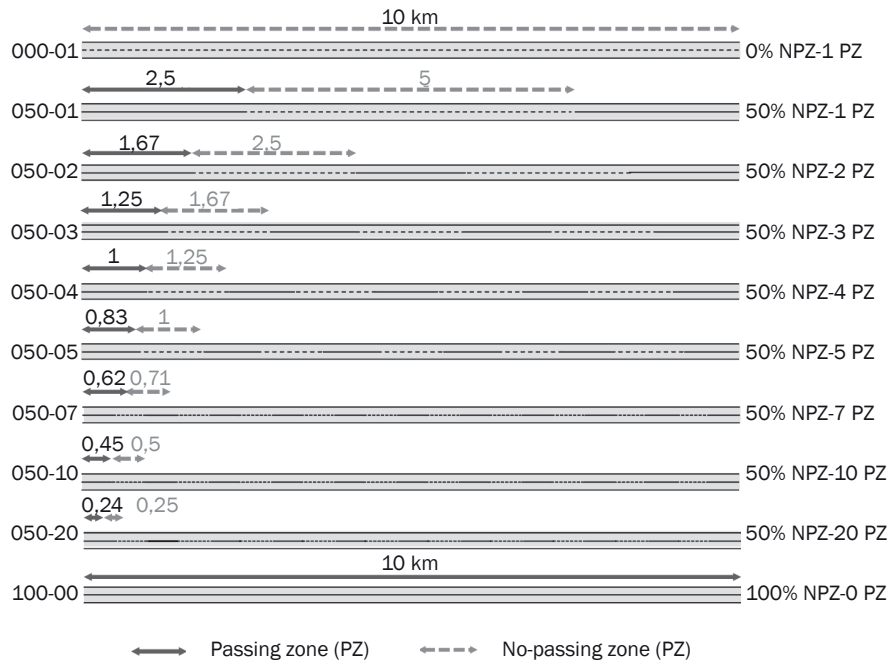


Figure 1 – Case study scenarios

- Directional traffic flow: between 100 and 1,700 veh/h at 50 veh/h increments. Opposing traffic flow was calculated and limited to 1,700 veh/h or two-way traffic flow of 3,200 veh/h.
- Percentage of heavy vehicles: 0, 10, 20, and 30%.
- Randomness: 15 replications. Random number seeds for entering headways, desired speeds, and driving behavior were selected among a sample of 25, while the combination of calibration parameters was selected among the best 50 combinations of the calibration.

The total number of simulations was 128,700 (257,400 directional scenarios). The maximum directional traffic flow was 1,540 veh/h (with 0% heavy vehicles), as higher traffic flows stalled TWOPAS. Therefore, the number of valid directional scenarios was reduced to 249,150.

2.4 Modeling base conditions

Two performance measures are analyzed: *ATS* and *PTSF*. Passenger car units from the HCM are not used. Instead, the effect of heavy vehicles is applied through the percentage of heavy vehicles, similar to the German procedure, but classified as a continuous variable. The values are obtained from the TWOPAS output file (*.OUT).

Base conditions (i.e., no passing restrictions) are modeled first for *ATS* and *PTSF*. They correspond to scenario 000-01. The statistical summary of the models is provided on the supplementary materials.

The resulting best model for *ATS* is the same type as HCM 2010, i.e., linear model considering directional traffic flow rate, opposing traffic flow rate, and percent

of heavy vehicles (Equation 2). The correlation between fitted and simulation values is 94%. The package NLS from the statistical software R is used for the statistical analysis [29].

$$ATS_{base} = FFS - 0.01504 \cdot V_d - 0.0064 \cdot V_o \cdot 0.0522 \cdot HV_d \tag{2}$$

where:

- ATS_{base} – the average travel speed for base conditions (i.e., 0% no-passing zones) [km/h];
- FFS – the free-flow speed [km/h]. In this case, the coefficient of the model indicated that the free flow speed amounted to 89.52 km/h;
- V_d – the directional traffic flow rate [veh/h];
- V_o – the opposing traffic flow rate [veh/h];
- HV_d – the percent of heavy vehicles in the analysis direction [%].

The $PTSF_{base}$ exponential model exhibits the strongest correlation to simulation results (97%), pseudo R^2 (95%), and minimum Akaike Information Criterion (AIC) (Equation 3). The model is of the same type as the HCM. The correlation is 98%. The exponential model was developed using the package NLS from the statistical software R [29].

$$PTSF_{base} = 100 \cdot (1 - \exp(a \cdot V_d^b)) \tag{3}$$

$$a = -2.12 \cdot 10^{-3} - 3.48 \cdot 10^{-5} \cdot V_o + 6.15 \cdot 10^{-4} \cdot \ln(V_o) \tag{3a}$$

$$b = 1.33 - 2.33 \cdot 10^{-5} \cdot V_o - 0.1 \cdot \ln(V_o) \tag{3b}$$

where $PTSF_{base}$ is the percent time spent following for base conditions (i.e., 0% no-passing zones) [%]; a and b are coefficients. Other terms are as previously defined.

2.5 Modeling the effect of percentage of no-passing zones

The effect of percentage of no-passing zones (*NPZ*) is evaluated using scenarios 000-01 (base scenario), 050-01 (50% *NPZ*), and 100-00 (100% *NPZ*).

The adjustment factors for *ATS* and *PTSF* depending on *NPZ* (ATS_{NPZ} and $PTSF_{NPZ}$) are modeled as the difference between simulation results and estimates for the reference scenario (000-01). Different combinations of independent variables and functional forms are executed in the R statistical software tool using the NLS package [29]. AIC (Akaike Information Criterion), correlation between fitted values and simulation values, beta parameters, p-value of the variables, and number of parameters are then used to determine the best model at each case. Coefficient of determinations and pseudo R^2 are added only to linear regression models. The statistical summary of the best model for each case is provided on the supplementary materials.

Average travel speed

The best model to estimate the effect of *NPZ* on *ATS* is polynomic and considers directional traffic volume, opposing traffic volume, percentage of heavy vehicles and percentage of no-passing zones (Equation 4). Pseudo R^2 is 33.7%, and the correlation between the fitted and simulation values is 58%.

$$ATS_{NPZ} = 2.06 - 0.017 \cdot V_d - 0.064 \cdot P_{NPZ} + 0.027 \cdot HV_d + 2.92 \cdot 10^{-5} \cdot V_d^2 - 1.45 \cdot 10^{-8} \cdot V_d^3 + 5.43 \cdot 10^{-5} \cdot P_{NPZ} \cdot V_o \tag{4}$$

where ATS_{NPZ} is the *ATS* adjustment factor for percentage of no-passing zones [km/h]; P_{NPZ} is the percentage of no-passing zones [%]. Other terms are as previously defined.

ATS decreases as the percentage of no-passing zones (*NPZ*) increases (Figure 2). The effect of passing restrictions is very small in unbalanced directional splits (lower than 40/60), with reductions lower than 2 km/h. As directional split becomes more balanced, the effect is greater, up to 5 km/h. The maximum effect is produced at directional traffic volumes between 200 and 400 veh/h, where the passing rate is relatively high.

For all directional splits, the differences are practically zero at high directional traffic volumes. Passing zones are essentially no longer effective for balanced flows with directional traffic volume higher than 800 veh/h.

Percent time spent following

The best model to estimate the effect of *NPZ* on *PTSF* includes the directional traffic flow rate, opposing traffic flow rate, and percentage of no-passing zones (Equation 5). The correlation between the fitted and simulation values is 85%.

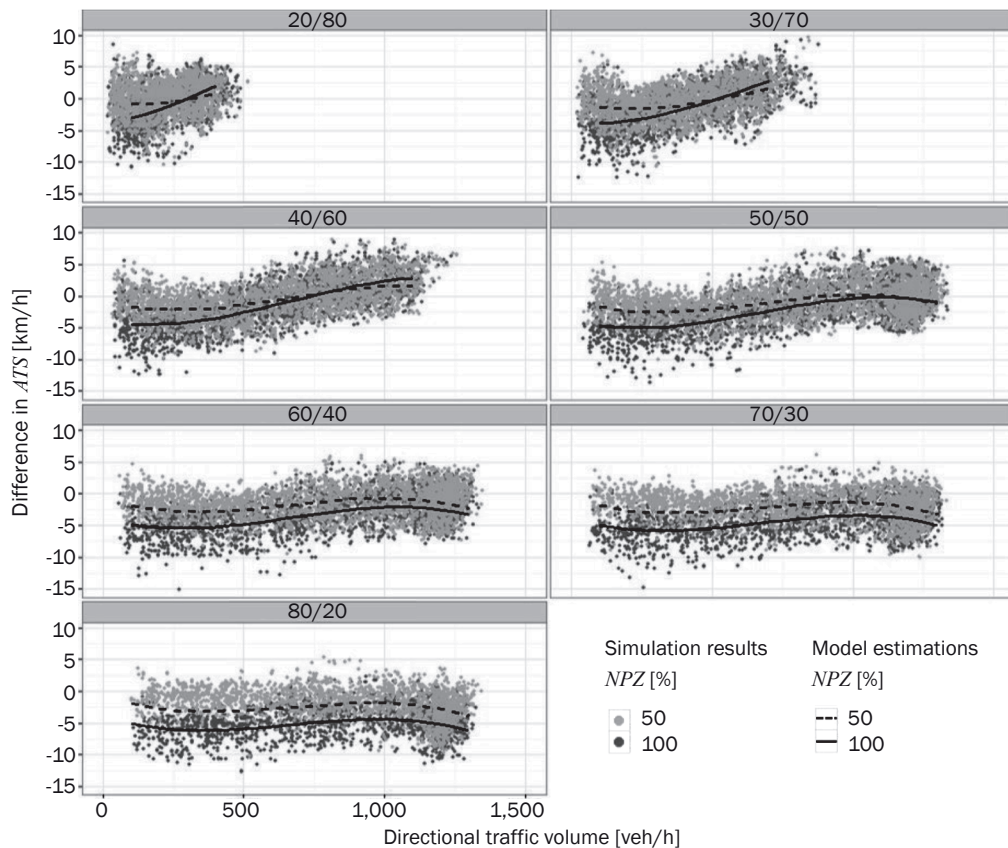


Figure 2 – Difference in *ATS* depending on percentage of no-passing zones

$$PTSF_{NPZ} = \frac{-26.86 + 0.122 \cdot V_d + 0.573 \cdot P_{npz} - 0.025 \cdot V_o}{1 + \exp(0.0025 \cdot V_d - 0.0106 \cdot P_{npz} + 0.0037 \cdot V_o)} \quad (5)$$

where $PTSF_{NPZ}$ is the $PTSF$ adjustment factor for percentage of no-passing zones [%]. Other terms are as previously defined.

The effect of NPZ is higher for $PTSF$ than for ATS (Figure 3). For low traffic volumes, increasing NPZ can increase $PTSF$ up to 40 %. The differences increase as the directional split is more balanced. For directional splits below 40/60, $PTSF$ is practically equal on the base conditions and 50% NPZ , and the difference is up to 20% for 100% NPZ . For balanced flows, the influence is maximized for directional traffic volume of 200 veh/h: 7% and 23% increases in $PTSF$ for 50% and 100% NPZ , respectively. As the directional split is less balanced, the differences are greater, and the maximum influence moves to higher directional volumes, between 250 and 350 veh/h.

On the other hand, the $PTSF$ -improving effect of passing zones disappears at high traffic volumes. The exact value depends on the directional split: 400 veh/h for 30/70, 800 veh/h for 50/50, and 1,250 veh/h for 70/30.

2.6 Modeling the effect of average passing zone length

Given the high differences on $PTSF$ between 50% NPZ and 100% NPZ , the effect of average passing zone length (PZL) is also analyzed. Only adjustment

factors for $PTSF$ are modeled because the influence of passing restrictions on ATS is quite low and comparable to the dispersion of the variable.

As in Section 2.5, the adjustment factor for $PTSF$ depending on PZL ($PTSF_{PZL}$) is calculated as the difference between simulation results and estimates for the reference scenario (050-01). Then, different combinations of independent variables and functional forms are tested.

The best model for $PTSF_{PZL}$ includes the directional traffic flow rate, opposing traffic flow rate, and average passing zone length (Equation 6). The correlation between the fitted and simulation values is 63%. The difference to the reference scenario (050-01, one passing zone of 5,000 m) was used to evaluate the effect of reducing the passing zone length.

$$PTSF_{PZL} = \frac{-39.79 + 0.0046 \cdot V_d + 0.0128 \cdot (5000 - L_{PZ}) + 0.0035 \cdot V_o}{1 + \exp(0.0016 \cdot V_d - 0.00036 \cdot (5000 - L_{PZ}) + 0.0043 \cdot V_o)} \quad (6)$$

where $PTSF_{PZL}$ is the $PTSF$ adjustment factor for average passing zone length [%], and L_{PZ} is the average passing zone length [m]. Other terms are as previously defined.

Additionally, the difference between the model estimations for 50% NPZ and for 100% NPZ is calculated to compare with total passing restrictions (Figure 4). The effect of PZL is quite strong. Very short passing zones (250 m, in dark blue) produced similar results as total passing restrictions (100% NPZ , in black). On those conditions, $PTSF$ values increase up

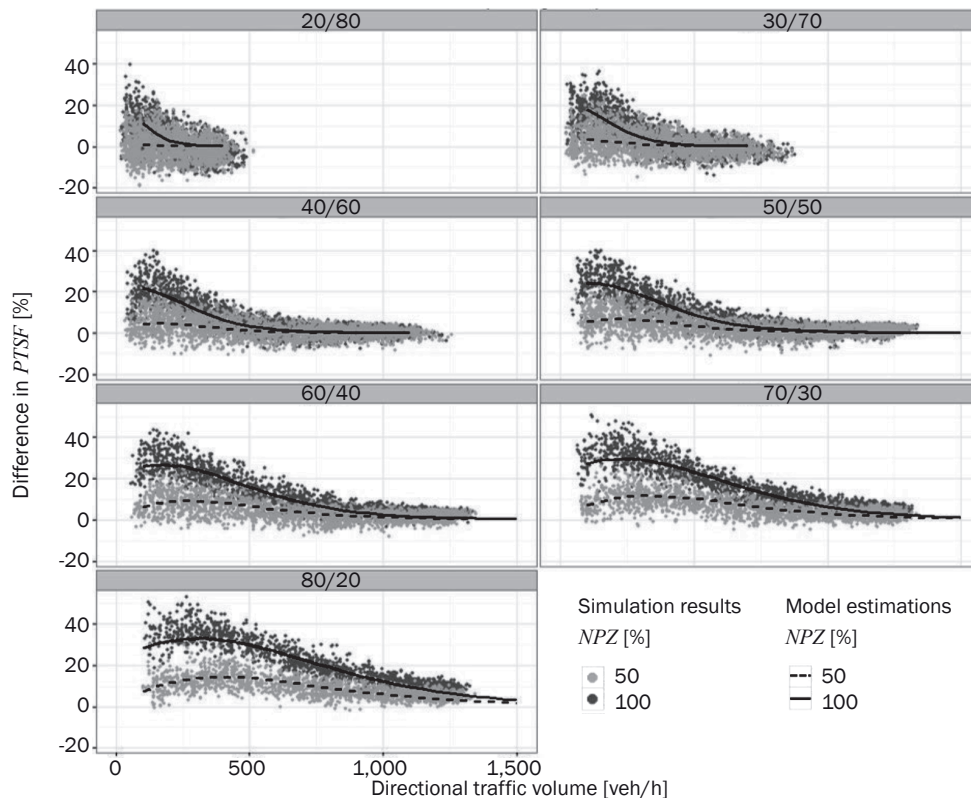


Figure 3 – Difference in $PTSF$ depending on percentage of no-passing zones

to 20%, even though they have the same percentage of no-passing zones. On the other hand, the difference between 2,500 and 5,000 m is practically zero. Therefore, increasing the passing zone length beyond 2,500 m does not improve traffic performance.

Similarly to NPZ, differences disappear at high traffic volumes. The value depends on the directional split and increases as it becomes more favorable. As seen, the difference decreases as the directional traffic flow rate increases, as passing opportunities decrease on the opposing lane. From that traffic demand, increasing average passing zone length will not improve traffic performance. The exact traffic demand where passing zones are no longer effective depends on directional split: 400 veh/h for 30/70; 800 veh/h for 50/50, and 1,250 veh/h for 70/30.

3. DISCUSSION

The effect of passing restrictions on *ATS* is quite low. This result suggests a marginal effect on *ATS*, compared to other variables that directly affect speeds along curves, such as higher presence of curves with smaller radii. The result agrees with the simulation results in Germany [25]. Moreover, the difference between 50% of passing zones and no passing at all is lower than 3 km/h, and the dispersion of the variable

is around 5 km/h. Therefore, the influence of average passing zone length is not evaluated as the effect will be close to the dispersion of the variable.

Simulation results are compared to HCM estimates for *ATS*. Average differences are calculated and plotted depending on directional traffic volume, directional split, and average passing zone length (Figure 5). Differences are lower than 2 km/h on average for passing zones longer than 1,250 m and directional splits over 60/40. For different conditions, differences can be up to 8 km/h.

The *PTSF*-improving effect of passing zones disappears at high traffic volumes or when opposing traffic volume is significantly higher than directional traffic volume. The model estimates differences greater than zero for average passing zone lengths shorter than 2,000 m. Therefore, increasing passing zone length beyond 2,000 m does not improve operational efficiency, regardless of directional split. For balanced flows, reducing passing zones from 5,000 m to 1,000 m only increases *PTSF* up to 5%. *PTSF* increases by 11.7% for passing zones of 500 m, compared to passing zones of 5,000 m. Conversely, very short passing zones contribute very little to traffic efficiency and have similar results as total passing restrictions.

Simulation results are compared to HCM estimates for *PTSF*. Similar to *ATS*, average differences are calculated and plotted (Figure 6). Differences between

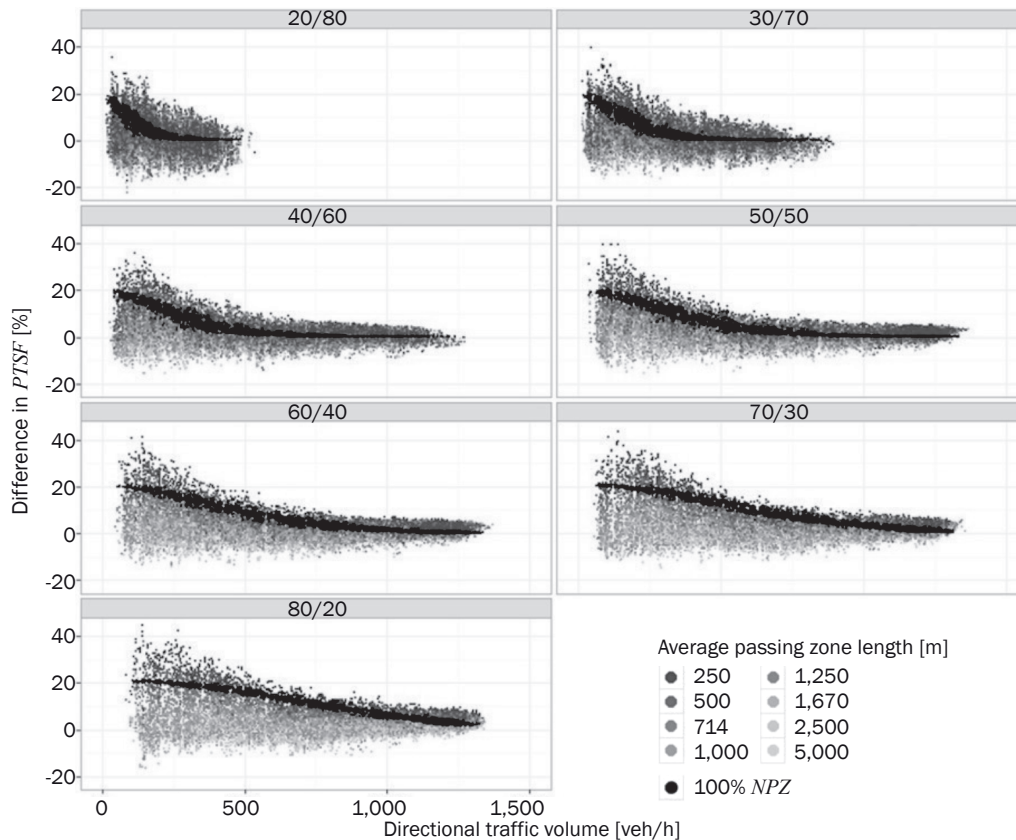


Figure 4 – Difference in *PTSF* depending on average passing zone length

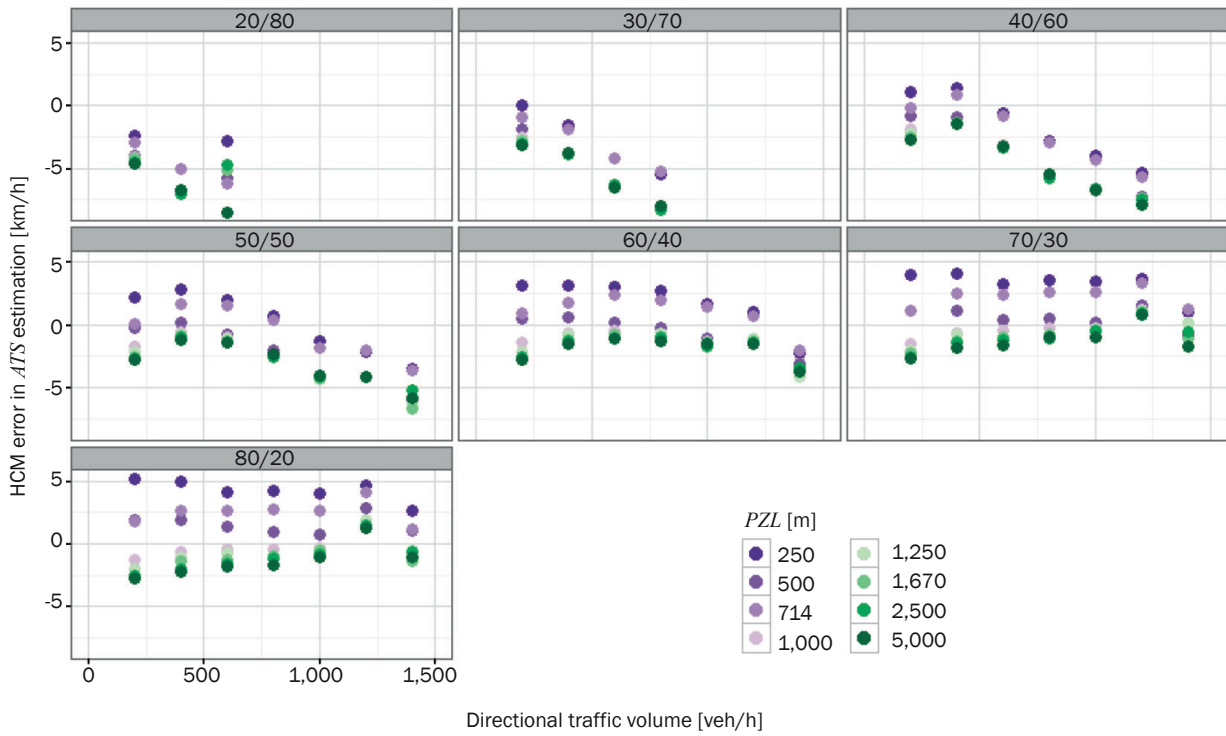


Figure 5 – HCM average error in ATS estimation

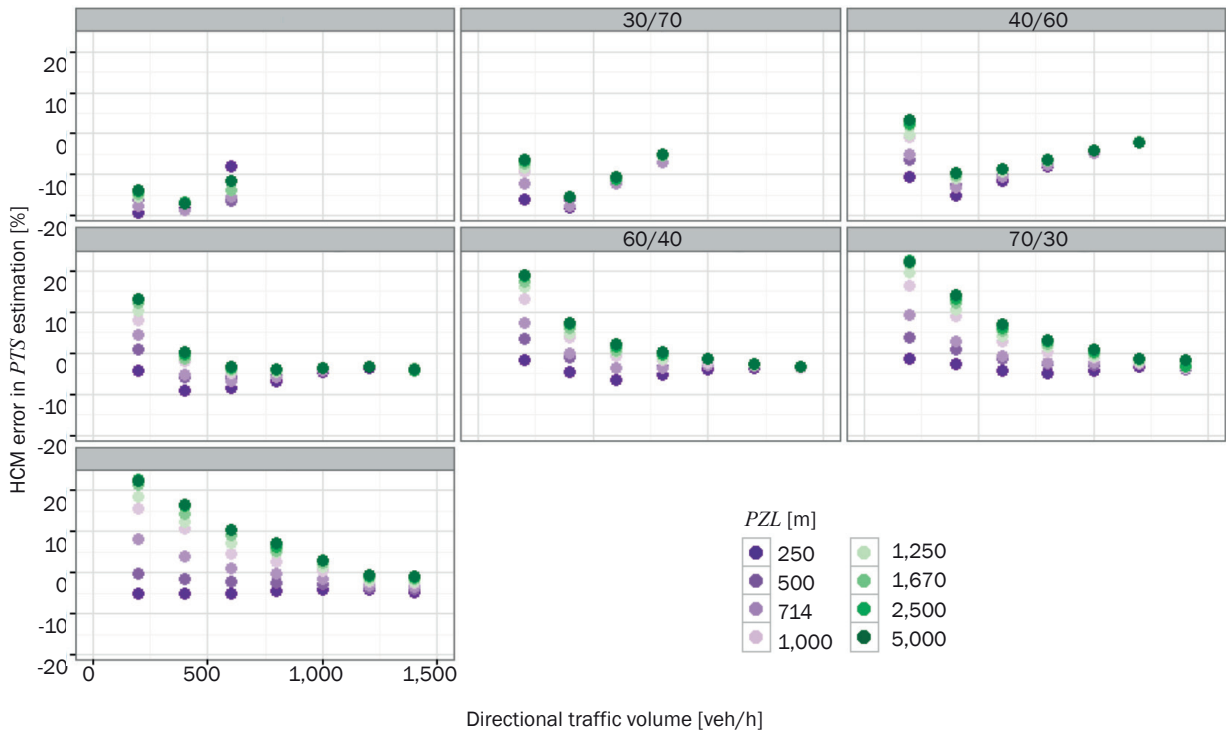


Figure 6– HCM average error in PTSF estimation

HCM estimates and simulation results vary between -20% and +25%. For directional splits below 50/50, HCM underestimates *PSTF*, while for directional splits over 50/50, it overestimates *PSTF*. The differences are greater as the directional split is more unbalanced.

For directional splits over 50/50, the overestimation is greater at low directional traffic volumes and passing zones longer than 714 m. In fact, HCM estimates are very close to the simulation results for *PZL* zones of 500 m, for directional splits over 50/50.

4. CONCLUSION

The research evaluates the influence of passing restrictions on two-lane traffic performance. Current passing behavior was collected in passing zones with a posted speed limit of 100 km/h. The TWOPAS microsimulation program was calibrated with a genetic algorithm and validated with additional field data. Then it was applied to different scenarios with varying directional traffic flow, directional split, percentage of heavy vehicles, and passing restrictions.

The conclusions of the study are:

- Passing restrictions had little effect on *ATS*, and it is marginal compared to other variables, such as higher presence of curves. The difference between no passing restrictions and total passing restriction (100% *NPZ*) is lower than 6 km/h; between 50% *NPZ* and 100% *NPZ* it is lower than 2 km/h. Therefore, using only the percentage of no-passing zones to model passing restrictions' effect on *ATS* may be adequate for straight segments.
- The effect of passing restrictions on *PTSF* is considerable, being up to 30%. The differences increase as the directional split becomes more unbalanced (50/50 - 80/20). The *PTSF*-improving effect of passing zones disappears at high traffic volumes, around 800 veh/h, for balanced flows (50/50).
- Both percentage of no-passing zones and average passing zone length should be included in the analysis to evaluate *PTSF*. Increasing the passing zone length beyond 2,000 m does not improve *PTSF*, while passing zones shorter than 250 m do not contribute to operational efficiency and produce the same traffic performance as total passing restriction.

Based on these conclusions, the recommendations of the study are:

- *ATS* can be calculated using *Equations 2 and 4*. *PTSF* can be calculated using *Equations 3, 5, and 6*. This methodology is simpler than the HCM methodology and accounts for the effect of average passing zone length in *PTSF*.
- Application of HCM equations to the analysis of Spanish two-lane highways is not recommended. Minor differences were observed for *ATS*.

While the use of simulation provides sufficient repeatability for the full range of traffic demands and passing restrictions, the results are subject to some degree of uncertainty. They could be derived from the structure of the model, the values of the model parameters, or methodological choices, such as case study scenario definition. Calibration and validation of the model are crucial to reduce the degree of uncertainty, as well as using multiple random seeds. The conclusions of the study are limited to the observed and generated simulation scenarios in TWOPAS: two-lane highways with 100 km/h posted speed limit,

level terrain, straight segments, and good pavement conditions. Other highways with higher presence of curves or considerable passing restrictions may need local adaptation. The extrapolation of these results to other geographical areas should be undertaken with caution, since drivers' behavior may vary. Other software could provide different results derived from their specific structure and their passing acceptance model. It is beyond the scope of this paper to compare calibrated traffic microsimulation software and its results on traffic performance measures. By using the same software as Harwood et al. [13, 14], we minimized the impact of such limitation.

Finally, the most appropriate performance measure for two-lane highways is still open for discussion. Field studies indicated that follower density was the most promising performance measure, as it presented the highest correlation to traffic variables. Further research will be needed to model alternative performance measure(s), such as density, follower density, or percent impeded, and under different geometric conditions, such as posted speed limit, terrain, or horizontal alignment.

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CONSIDERACIONES OPERACIONALES DE LAS ZONAS DE ADELANTAMIENTO EN CARRETERA CONVENCIONAL: CASO DE ESPAÑA

RESUMEN

La metodología que se emplea en España para la evaluación de la funcionalidad del tráfico y la determinación del nivel de servicio es el Manual de Capacidad de Estados Unidos (Highway Capacity Manual – HCM 2010). En carreteras convencionales, las restricciones al adelantamiento se consideran a partir del porcentaje de zonas de adelantamiento no permitido. Esta medida no tiene en cuenta la distracción de las zonas de adelantamiento en el segmento. El objetivo de la investigación es la evaluación del efecto del porcentaje de adelantamiento no permitido y la longitud media de las zonas de adelantamiento en la funcionalidad del tráfico, y, en caso de ser significativos, incorporarlos a la metodología. El programa de microsimulación TWOPAS se ha calibrado y validado para las condiciones españolas. Las restricciones al adelantamiento tienen escaso efecto en la velocidad media, con unas diferencias inferiores a 6 km/h entre un segmento sin restricciones al adelantamiento y otro con restricción total. Por otro lado, las restricciones al adelantamiento pueden incrementar el porcentaje de tiempo en cola hasta un 30%. Aumentar la longitud media de las zonas de adelantamiento a partir de 2,000 m no mejora el porcentaje de tiempo en cola. Los nuevos modelos se pueden emplear para estimar la funcionalidad del tráfico en carreteras convencionales españolas.

PALABRAS CLAVE

Funcionalidad del Tráfico; Carretera Convencional; Porcentaje de Tiempo en Cola; Velocidad Media; Restricción de Adelantamiento; Zona de Adelantamiento;

REFERENCES

- [1] American Association of State Highway and Transportation Officials. *A Policy on Geometric Design of Highways and Streets*. 6th ed. Washington, DC: American Association of State Highway and Transportation Officials; 2011.
- [2] Ministerio de Fomento. *Instrucción de Carreteras Norma 3.1 IC: Trazado*. Madrid; 1999.
- [3] Polus A, Livneh M, Frischer B. Evaluation of the Passing Process on Two-Lane Rural Highways. *Transportation Research Record: Journal of the Transportation Research Board*. 2000;1701: 53-60. Available from: <https://doi.org/10.3141/1701-07>
- [4] Harwood DW, Gilmore DK, Richard KR, Dunn J, Sun C. *NCHRP 605 Passing Sight Distance Criteria*; 2008. Available from: <http://docs.trb.org/prp/10-2621.pdf>
- [5] Llorca C, Moreno AT, Sayed T, García A. Sight Distance Standards Based on Observational Data Risk Evaluation Of Passing. *Transportation Research Record: Journal of the Transportation Research Board*. 2014;2404: 18-26. Available from: <http://www.scopus.com/inward/record.url?eid=2-s2.0-84904821955&partnerID=tZ0tx3y1>
- [6] Kaub AR. Passing Operations on a Recreational Two-Lane, Two-Way Highway. *Transportation Research Record: Journal of the Transportation Research Board*. 1990;1280: 156-62. Available from: <http://onlinepubs.trb.org/Onlinepubs/trr/1990/1280/1280-017.pdf>
- [7] Romana MG. Passing Activity on Two-Lane Highways in Spain. *Transportation Research Record: Journal of the Transportation Research Board*. 1999;1678: 90-5. Available from: <https://doi.org/10.3141/1678-12>
- [8] Hegeman G. Overtaking Frequency. *Proceedings of the IEEE International Conference on Systems, Man and Cybernetics*; 2004. Volume 4. p. 4017-4022, Available from: <https://doi.org/10.1109/ICSMC.2004.1400972>
- [9] Mwesige G, Farah H, Bagampadde U, Koutsopoulos HN. A Stochastic Model for Passing Rate at Passing Zones on Two-Lane Rural Highways in Uganda. *Proceedings of the 93rd Annual Meeting of the Transportation Research Board, 12-16 January 2014, Washington, D.C., USA*; 2014.
- [10] Moreno AT, Llorca C, García A, Pérez-Zuriaga AM. Operational Effectiveness of Passing Zones depending on their Length and Traffic Volume. *Transportation Research Record: Journal of the Transportation Research Board*. 2013;2395: 57-65. Available from: <https://doi.org/10.3141/2395-07>
- [11] Mwesige G, Farah H, Bagampadde U, Koutsopoulos HN. Effect of passing zone length on operation and safety of two-lane rural highways in Uganda. *IATSS*. 2017;41(1): 38-46. Available from: <https://doi.org/10.1016/j.iatssr.2016.09.001>
- [12] Transportation Research Board. *Highway Capacity Manual*. Washington, DC: Transportation Research Board; 2010.
- [13] Harwood DW, May AD, Anderson IB, Leiman L, Archilla AR. *Capacity and Quality of Service of Two-Lane Highways*, NCHRP project 3-55, 1999. Available from: <http://docs.trb.org/prp/16-5259.pdf>
- [14] Harwood DW, Potts IB, Bauer KM, Bonneson JA, Elefteriadou L. *Two-Lane Road Analysis Methodology in the Highway Capacity Manual*, NCHRP project 20-7/Task 160, 2003.
- [15] Luttinen RT. Uncertainty in Operational Analysis of Two-Lane Highways. *Transportation Research Record: Journal of the Transportation Research Board*. 2002;1802: 105-14. Available from: <https://doi.org/10.3141/1802-13>
- [16] Luttinen RT. *Traffic Flow on Two-Lane Highways. An Overview*. Lahti, Finland: TL Consulting Engineers, Ltd.; 2001.
- [17] Luttinen RT. Percent Time-Spent-Following as Performance Measure for Two-Lane Highways. *Transportation Research Record: Journal of the Transportation Research Board*. 2001;1776: 52-9. Available from: <https://doi.org/10.3141/1776-07>
- [18] Bessa JEJ, Setti JR. Derivation of ATS and PTSF Functions for Two-lane, Rural Highways in Brazil. *Procedia – Social and Behavioral Sciences*. 2011;16: 282-92. Available from: <https://doi.org/10.1016/j.sbspro.2011.04.450>
- [19] Bessa JEJ, Setti JR., Washburn, S. Evaluation of Models to Estimate Percent Time Spent Following on Two-Lane Highways. *Journal of Transportation Engineering Part A – Systems*. 2017;143(5). Available from: <https://doi.org/10.1061/JTEPBS.0000032>

- [20] Maldonado MO, Herz M, Galarraga J. Modelación de operación en carreteras argentinas y recomendaciones de ajustes al Manual de Capacidad HCM 2010. *Transportes*. 2012;20(3):51–61. Available from: <http://dx.doi.org/10.4237/transportes.v20i3.556>
- [21] Penmetsa P, Ghosh I, Chandra S. Evaluation of Performance Measures for Two-Lane Intercity Highways under Mixed Traffic Conditions. *Journal of Transportation Engineering*. 2015;141(10): 1-7. Available from: <http://ascelibrary.org/doi/full/10.1061/%28ASCE%29TE.1943-5436.0000787>.
- [22] Moreno AT, Llorca C, Washburn SS, Bessa JEJ, Hale DK, Garcia A. Modification of the Highway Capacity Manual Two-Lane Highway Analysis Procedure for Spanish Conditions. *Journal of Advanced Transportation*. 2016;50: 1650-1665. Available from: <https://doi.org/10.1002/atr.1421>
- [23] Forschungsgesellschaft für Strassen und Verkehrswesen. *Handbuch für die Bemessung von Strassenverkehrsanlagen* (HBS Edition 2015). Cologne: FGSV; 2015.
- [24] Forschungsgesellschaft für Strassen und Verkehrswesen. *Handbuch für die Bemessung von Strassenverkehrsanlagen* (HBS Edition 2001). Cologne: FGSV; 2001.
- [25] Weiser F, Jäger S, Riedl C, Lohoff J. *Verkehrstechnische Bemessung von Landstraßen – Weiterentwicklung der Verfahren*, BAST-Bericht V 263, 2011. Available from: https://www.bast.de/BAST_2017/DE/Publikationen/Berichte/unterreihe-v/2016-2015/v263.html
- [26] Harwood DW, Gilmore DK, Richard KR. Criteria for Passing Sight Distance for Roadway Design and Marking. *Transportation Research Record: Journal of the Transportation Research Board*. 2010;2195: 36-46. Available from: <https://doi.org/10.3141/2195-05>
- [27] Moreno AT, Llorca C, Lenorzer A, Casas J, García A. Design Criteria for Minimum Passing Zone Lengths. Operational Efficiency and Safety Considerations. *Transportation Research Record: Journal of the Transportation Research Board*. 2015;2486: 19-27. Available from: <https://doi.org/10.3141/2486-03>
- [28] Al-Kaisy A, Durbin C. Platooning on Two-lane Two-way Highways: An Empirical Investigation. *Procedia – Social and Behavioral Sciences*. 2011;16: 329-39. Available from: <https://doi.org/10.1016/j.sbspro.2011.04.454>
- [29] Baty F, Charles S, Flandrois J. The R package nlstools: A toolbox for nonlinear regression. *Journal of Statistical Software*. 2015;66(5): 1-21. Available from: <http://doi.org/10.18637/jss.v066.i05>