Design Criteria for Minimum Passing Zone Lengths: Operational Efficiency and Safety Considerations

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ABSTRACT

Passing zones are provided to improve operational efficiency of two-lane highways where passes can be performed safely. Minimum passing zone lengths of 120 m were established in MUTCD and Green Book, although some studies indicate a potential need to increase them. However, no changes have been recommended pending further research on the safety of short passing zones.

The objective of this study is to develop design and marking criteria for minimum passing zone lengths that consider traffic operational efficiency and safety.

In the first part of this study, a traffic microsimulation was carried out with Aimsun software. The calibration and validation included the observation of 1,750 passing maneuvers in Spain. The results indicate that passing zones shorter than 250 m add very little to operational efficiency. In the second part of the study, a reliability analysis was applied. It quantified the probability that a passing maneuver was completed beyond the end of the passing zone (non-compliant passing maneuvers). Afterwards, the number of non-compliant passing maneuvers was calculated. Traffic flow as well as passing zone length were contributing factors..

Findings from the analysis indicate that the minimum passing zone length should be increased to a minimum of 275 m, for high traffic volumes, 300 m for medium traffic volumes and 350 m for low traffic volumes. From this length, the number of non-compliant passing maneuvers decreases. The marginal increase in the minimum length of passing zones can potentially improve safety without significantly reducing the operational efficiency. The results can be directly used by practitioners to establish the minimum passing zone length based on the range of hourly volumes and the level of risk willing to assume.

INTRODUCTION

Passing sight distance (*PSD*) is a key consideration in the design of two-lane highways and the marking of passing and no-passing zones on two-lane highways *(1)*. The *PSD* criteria are used in the design and marking processes to ensure that sight distance and passing zone length is enough to safely perform passing maneuvers, where oncoming traffic permits. Passing zones allow faster vehicles to pass slower vehicles, thus improving the level of service on the highway.

Table 1 provides minimum passing zone lengths from the geometric design and marking standards for Spain *(2, 3)* and the US *(4–6)*. Generally, the values come from deterministic approaches *(7, 8)*, where risk has not been taken into account and conservative percentiles of variables have been selected.

Table 1. Minimum passing zone length

Country - Standard	Minimum passing zone length (m) at reference speed (km/h)									Reference Speed
	40	**50**	**60**	**70**	**80**	**90**	**100**	**110**	**120**	
Spain design criterion (2000) *(2)*	not provided									*Vd*
Spain marking criterion (1987), ***Table 1*** *(3)*	50	75	100	130	165	205	250	n/a	n/a	*VM*
US AASHTO Green Book (2004) *(4)*	not provided									*Vd*
US AASHTO Green Book (2011), ***Table 3-5*** *(5)*.	120	180	210	240	240	240	240	240	240	*V85 or VM*
US MUTCD (2009), ***Page 354*** *(6)*	120	120	120	120	120	120	120	120	120	*V85*
Vd: design speed, *VM*: posted speed limit, *V85*: 85th percentile of operating speed										

In general, passing zone criteria define a minimum passing sight distance that must available to allow passing. Additionally, this passing sight distance must be available along a certain length. This research focuses on this minimum passing zone length. As shown in Table 1, only some criteria provide a minimum passing zone length value.

According to experimental data collected by Harwood et al. *(1)*, 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. Moreover, they performed a traffic microsimulation in TAM (Traffic Analysis Module of the Interactive Highway Safety Design Manual - IHSDM, previously named TWOPAS) to evaluate the contribution of short passing zones to the operational efficiency of two-lane highways. Scenarios involved a 4.8 km two-lane tangent highway with one passing zone in the middle of the segment. The passing zone length varied from 120 to 300 m and the directional traffic volumes between 100 and 600 veh/h. The results indicated that the passing zones did not alter much average travel speed nor percent time spent following. Furthermore, the maximum passing frequency of 2 passes per hour was obtained for traffic flows of 300 veh/h at 240 m passing zone length. Shorter passing zones provided much more limited passing frequencies. These facts could lead to the elimination of short passing zones. However, they stated that the elimination of these passing zones might lead to illegal passing maneuvers and it would reduce the opportunity for some flying passes and passes of slow-moving vehicles; and there were not studies that showed crash patterns associated with passing maneuvers in short passing zones. Consequently, only limited changes in the MUTCD minimum passing zone length were recommended, pending further research on the safety of short passing zones.

This report could reflect some concerns. On one hand, authors did not validate TAM with this study, assuming TAM initial calibration based on 1970's data *(9)*. Moreover, the number of passing maneuvers was very little, compared to other field studies *(10–13)*. The difference on traffic flows, directional split, passing zone length and maybe local driver behavior resulted in dispersion on the number of passes. The passing zone lengths were generally higher than 500 m, so the conclusions may not be representative for short passing zones. Only two studies included short passing zones *(1, 10)*, with different passing frequencies. Harwood et al. *(1)* covered more short passing zone lengths, while Moreno et al. *(10)* observed more range of traffic flows. Thereafter, observational passing studies may not be applicable and traffic microsimulation may be needed.

There have been previous research focused on the development of passing models for traffic microsimulation. However, their level of detail, their validation or the fields of application are not homogeneous. TAM, CORSIM *(14)*, TWOSIM *(15, 16)*, RutSim *(13)*, Ghods *(17)* and Aimsun *(18)* incorporated passing maneuvers to the two-lane highway module. However, most of them are still not validated with detailed observations of passing maneuvers. Llorca et al. *(19)* developed a passing model based on the results of observation of 1,750 passing maneuvers, that was implemented in the Aimsun software. They incorporated the effect of new factors such as available sight distance, delay and remaining travel time until the end of the highway segment and the model was calibrated and validated with micro and macroscopic data.

On the other hand, the lack of statistics related to crash frequency on short passing zones does not verify that short passing zones are safe. Up to now, only two studies evaluated the safety of short passing zones *(1, 20)*. The oldest used data from three short passing zones and subjectively rated the severity of the return of the passing vehicle, from smooth return to forced return and violent return *(20)*. The proportion of forced and violent returns for 270 m long passing zone was 10%, and it increased to 45% at 200 m long passing zone. Harwood et al. *(1)* determined that 92% of passing maneuvers ended beyond the passing zone in short passing zones, compared to 21% of longer passing zones (over 300 m). However, the traffic volume range was narrow (100-260 veh/h) and very few passing maneuvers were observed.

An alternative approach is reliability analysis. This approach accounts the variability of design parameters, considering them as stochastic variables defined by their probability distributions rather than single values. It is based on the limit state design procedure, used frequently in structural engineering. The system is considered to fail when the demand (i.e. required passing sight distance) exceeds the supply (i.e. actual passing sight distance). El Khoury and Hobeika *(21, 22)* first defined the methodology to apply reliability to passing sight distance. El-Bassiouni and Sayed *(23)* concluded that AASHTO standards had a probability of noncompliance of 18% at the design speed of 100 km/h. They used probabilistic distributions of input parameters based on a literature review *(21, 22)* or on a driving simulator experiment *(23)*. Llorca et al. *(24)* used passing maneuver observations *(25, 26)* to characterize the input parameters and to develop the passing model. The results of the reliability analysis showed that geometric design standards presented a probability of noncompliance of about 15 %, while some of the marking standards had probability of non-compliance exceeding 85 %. These standards may be associated with higher risk levels if they were followed by drivers. Nevertheless, the risk was not correlated with the actual use of the passing zones.

Research motivation

Some consideration would still need to be given to the potential for safety improvement from marginal changes in the minimum length of passing zones, considering also their use. Therefore, there is a need to update the operational contribution of short passing zones; and to incorporate risk-based criteria to evaluate the safety level at short passing zones.

OBJECTIVES

The aim of the study is to develop design and marking criteria for minimum passing zone length based on both operational and safety impacts. The specific objectives are:

- Evaluate the contribution of short passing zones to the operational efficiency of a two-lane highway.
- Determine minimum passing zone lengths accounting their use and safety.

OPERATIONAL CONTRIBUTION OF SHORT PASSING ZONES

The methodology and the results of this part were based on a new passing maneuver model. The model is part of the microsimulation software Aimsun, and was developed, calibrated and validated using passing maneuver field data *(19)*. The model was applied to more than 39,000 directional scenarios varying: passing zone length; traffic volume; entry percent of followers; and, replications. The passing model, case study scenarios and results will be described on the following sections.

Passing model in Aimsun

This section will summarize the passing model in Aimsun. Further details can be found in Llorca et al. *(19)*.

Passing is a complex task involving several driver decisions. Passing process is explained usually as a three-step process *(14, 27)*, starting when a vehicle enters in a platoon behind a slower vehicle:

- Passing desire, which considers driver's option to pass or to follow a slower vehicle without passing it.
- Passing decision, affecting driver's gap acceptance or rejection.
- Passing execution, affecting passing maneuver completion or abort.

The possibility to pass is considered at any simulation step for the vehicles that are in queue. A vehicle that cannot reach its desired speed is considered to be in a queue. The following subsections explain in detail the three passing stages.

Passing desire

The desire to pass depends on four variables: time spent following (*delay*), difference between desired speed and actual speed (*dV*), rank in the queue (*rank*) and remaining travel time to the end of the highway segment (*remaining time*).

Initially, for little *dV* the driver would accept the delay without desire to pass (*mindV*); while over a maximum *dV* threshold the pass will be desired independently of the delay (*maxdV*). Between those scenarios, increasing the delay will reduce the threshold that would make a driver desired to pass (Figure 1).

The probability of a driver to desire passing is also dependent on the position on the queue (*rank*) and the remaining travel time on the two-lane highway (Figure 1). Both effects reflect an observed behavior of reduced passing desire if there was more than one vehicle to be passed *(28)* and reduced passing frequency at passing zones close to the end of a two-lane highway.

If passing is desirable, the following gap is reduced by applying a car following factor to the Gipps model.

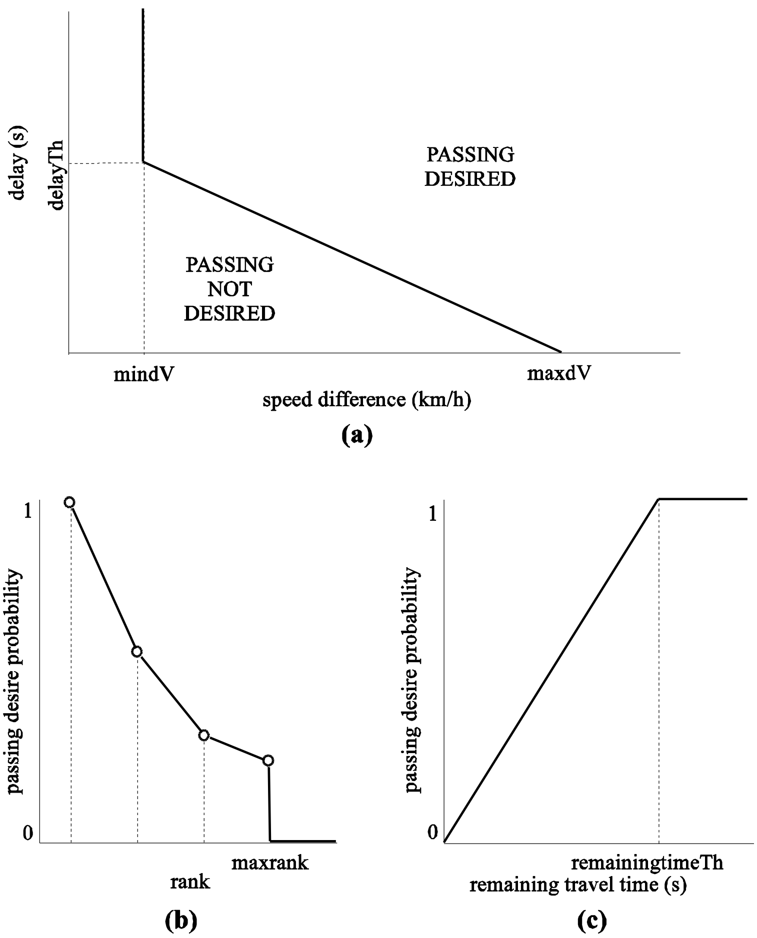

Figure 1. Passing desire in Aimsun software

<u>Passing decision</u>
Once passing is desired, the driver would decide whether to pass or not. The decision to pass includes various steps:

1. Verification that no-solid lines forbids passing maneuver.
2. Verification whether other vehicles are currently passing the leading vehicle. In this case, it takes into account whether simultaneous passing maneuver is allowed (*maxsimul* equal to 1 or over 1) and whether the delay between simultaneous passing maneuver is respected (*delaysimul*) or not.
3. Gap acceptance process, if the result of previous steps was positive.

Gap acceptance decision represents the comparison between available gap and required gap, which is evaluated at every simulation step. For this calculation (and later, during passing execution) it is assumed that passing vehicle maintains a constant acceleration until it reaches its desired speed, and after this point, it maintains a constant speed.

The possibility of exceeding the desired speed during passing (named passing vehicle enhanced speed, equal to the desired speed multiplied by the factor *PVSE* – passing vehicle speed enhancement) is considered. Those vehicles that have a *dV* under the passing vehicle speed enhancement threshold *PVSEth* would require a little extra speed to complete the maneuver while higher speed differences would be enough to complete the maneuver without speeding.

To evaluate the passing decision, the following variables are calculated:

- Passing time (*PT*): duration of the maneuver in the current conditions.

- Time to collision with the closest oncoming vehicle (*TC*). In case there is no oncoming vehicle, or it is located further away than the available sight distance at the position of the subject vehicle, an equivalent fictitious vehicle is located at the visibility edge. The observations indicated a higher passing frequency on sight distance-limited situations compared to oncoming vehicle-limited maneuvers *(29)*. As a consequence, the *SDfactor* was included. It generates an equivalent *TC* for cases without oncoming vehicles, multiplying the available sight distance by the *SDfactor*.
- Time to the end of passing zone (*TS* – time to sign): time to no-passing zone marking.

A passing gap is accepted if *PT* plus a safety margin (random variable different for each driver) is less than *TC*, and if *PT* is less than *TS*.

Passing execution

Once a gap is accepted, the vehicle accelerates and starts changing to the left lane. The feasibility of passing maneuvers is re-evaluated at every simulation step during the passing maneuver. An additional variable is calculated:

- Abort time (*AT*): is the time the passing vehicle requires to decelerate and return to its own lane without have passed the impeding vehicle.

Depending on the relation between *PT*, *AT*, *TC* and *safety margin*, four cases are possible:

1. The maneuver is not completed ($PT>0$) and there is no risk of collision ($PT+safetymargin < TC$): continue passing.
2. The maneuver is not completed ($PT>0$), there is a risk of collision ($PT+safetymargin \geq TC$) and the critical point has not been reached ($PT>AT$): abort maneuver.
3. The maneuver is not completed ($PT>0$), there is a risk of collision ($PT+safetymargin \geq TC$) and the critical point has been reached ($PT\leq AT$):
    a. The risk is not immediate: $TC>2\cdot Reactiontime$: continue acceleration to complete the maneuver, exceeding desired speed or enhanced speed if necessary.
    b. The risk is immediate: $TC\leq 2\cdot Reactiontime$: continue acceleration to complete the maneuver, exceeding desired speed or enhanced speed if necessary, and forcing impeding vehicle to decelerate.
4. The maneuver is completed ($PT=0$).

Calibration and validation of the Aimsun model

The Aimsun model was calibrated using microscopic and macroscopic data.

Two instrumented vehicles (passenger car and truck) collected in-detail data of 460 maneuvers during 26 h, on more than 90 passing zones located on 8 road segments *(25, 26)*. This data was used to characterize the following microscopic variables affecting passing decision and execution:

- Passing time (*PT*)
- Number of impeding vehicles
- Impeding vehicle average speed (*Vi)*
- Passing vehicle average speed (*Vp*)
- Passing vehicle instant speeds at the starting and at the ending point of the maneuver (*Vpstart, Vpend*)
- Opposing flow gap (*gap*)
- Safety margin between the end of the maneuver and the time when passing and oncoming vehicle crossed *(safetymargin*)

The parameters affecting passing decision and execution were calibrated. The comparison between simulated and observed passing time and passing vehicle speed distributions facilitated the selection of the car following reduction factor and the passing vehicle speed enhancement. The *RCF* factor was equal to 0.65, while *PVSE* was equal to 1.1 and *PVSEth* equal to 15 km/h. It means that vehicles travelling less than 15 km/h under their desired speed reach during passing a speed 10% higher than their desired speed.

Simulated and observed gap acceptance processes were compared using two probit binary choice models. This leaded to an 18.6 s average critical gap, and facilitated the selection of the *safetymargin* distribution. This variable was normal distributed, with a 5 s mean and a 3 s standard deviation. A minimum safety margin of 1 s was set according to the lower values in the observations. The higher probability of acceptance of sight distance-limited gaps resulted in a 1.75 *SDfactor*. It means that, for example, a sight distance gap of 1,750 m has the same probability of acceptance that a 1,000 m oncoming vehicle-limited gap.

A macroscopic calibration was also performed to verify the influence of passes on traffic performance. The macroscopic data were obtained from four passing zones ranging 265 to 1,270 m long, and hourly traffic volumes of 140 vph and 335 vph *(10, 25)*. Macroscopic data of traffic volume, percent followers and number of passing maneuvers characterized the operation of single passing zones. 15 replications of each scenario were performed and provided a 5% maximum relative error in the average 15-min traffic volumes, 15-min percent followers and a 4 passes maximum error, in the average hourly number of passes. In all the scenarios, the quality of the calibration was measured by the root mean square error RMSE of the hourly number of passes, which was minimized to 4.2 passes after the selection of the passing desire parameters (being the observed values within the range from 0 to 51 passes/hour). The values of the model parameters were *delayth* = 240 s, *mindV* = 10 km/h and *maxdV* = 35 km/h.

The calibration was carried out for single passing zones involving simple passing maneuvers. Therefore, the parameters *maxsimul*, *delaysimul* and *remainingtimeTh* were not considered.

Afterwards, the validation tested the model in four additional passing zones. In this case, the simulation results provided a RMSE equal to 1.6 passes, lower than the obtained in the calibration. This showed the ability of the model to represent a variety of passing zone characteristics.

Case study scenarios

The scenarios evaluated with Aimsun were similar to those studied by Harwood et al. *(1)*, but with wider traffic volume range and more replications per alternative. They involved a 5 km two-lane level, tangent road section, and one passing zone located at the middle of the section. Initially, seven passing zone lengths, from 100 to 400 m, were evaluated. One passing zone length of 500 m was added after the analysis of the first results, consequently, 8 passing zone lengths were considered. The passing zone alternatives were evaluated for 100 to 1,600 veh/h, with steps of 50 veh/h. Consequently, 31 traffic scenarios were generated covering the entire range of traffic volumes. A previous no-passing zone segment of variable length facilitated the generation of traffic streams with a variety of percent followers at the beginning of the segment.

In all cases, the directional split of traffic was 50/50 and only passenger cars were considered. A free-flow speed of 100 km/h was specified, according to the calibration. For each configuration and traffic volume, 15 replicate runs were made with the Aimsun model. The same sequence of replicates was run for each scenario. Due to the symmetrical scenario and traffic demand, both travel directions could be considered.

The Aimsun model provided a total of 44,640 directional scenarios.

Analysis and results

The preliminary analysis consisted of validating the directional scenario. Percent followers at the beginning of the passing zone was calculated and compared to the percent followers model

(30). This model was developed from observational data used in the calibration. Only the scenarios with a difference lower than 20% were included on the analysis: 41,347.

Table 2. Results of Aimsun simulations for short passing zones

	Traffic volume (veh/h)	**Passing zone length (m)**							
		100	**150**	**200**	**250**	**300**	**350**	**400**	**500**
Percent time spent following (%)	**100**	19.3	20.1	21.1	20.3	19.7	18.5	20.2	19.9
	200	35.0	35.5	34.7	35.4	34.7	35.8	35.1	36.5
	300	45.0	45.6	45.9	45.5	45.3	43.9	45.6	46.6
	400	51.8	52.5	52.1	52.4	53.0	52.4	52.5	55.6
	500	58.0	58.1	58.4	58.4	57.9	58.0	57.6	61.9
	600	63.5	62.7	63.1	63.1	63.0	63.7	63.1	66.5
	700	67.5	68.1	67.3	67.6	67.4	67.7	67.5	70.4
	800	71.0	71.2	71.0	70.8	70.8	71.0	71.1	74.0
	900	74.4	74.4	74.3	73.9	74.2	74.4	74.2	77.1
	1000	76.9	77.0	76.9	77.1	76.7	77.1	77.2	79.2
	1100	79.4	79.7	79.5	79.4	79.4	79.1	79.5	81.5
	1200	81.3	81.6	81.3	81.5	81.6	81.3	81.4	83.5
	1300	83.2	83.3	83.5	83.4	83.5	83.4	83.6	85.3
	1400	85.1	85.3	85.3	85.4	85.0	85.3	85.1	86.8
	1500	86.8	86.6	87.0	86.9	87.1	86.8	86.9	88.0
	1600	88.5	88.4	88.4	88.4	88.3	88.4	88.5	89.6
Average travel speed (km/h)	**100**	98.4	97.9	97.7	97.7	97.9	98.0	97.8	97.7
	200	96.2	95.8	96.2	96.0	96.2	95.8	96.0	95.8
	300	94.5	94.5	94.5	94.7	94.6	94.6	94.6	94.4
	400	93.7	93.5	93.6	93.5	93.5	93.4	93.6	93.0
	500	92.9	92.7	92.7	92.8	92.7	92.9	92.8	92.0
	600	91.9	92.1	92.0	92.0	92.1	91.8	92.0	91.3
	700	91.2	91.1	91.2	91.2	91.3	91.3	91.4	90.6
	800	90.7	90.7	90.8	90.6	90.8	90.8	90.7	90.1
	900	90.1	90.2	90.2	90.3	90.2	90.1	90.2	89.4
	1000	89.7	89.7	89.7	89.7	89.8	89.7	89.5	89.0
	1100	89.3	89.2	89.2	89.2	89.2	89.5	89.2	88.6
	1200	88.9	88.8	89.0	88.9	88.9	88.9	89.1	88.2
	1300	88.5	88.5	88.3	88.4	88.4	88.5	88.4	87.8
	1400	88.2	88.0	88.0	88.0	88.1	88.0	88.1	87.3
	1500	87.7	87.6	87.6	87.8	87.5	87.6	87.6	87.1
	1600	87.2	87.2	87.3	87.3	87.2	87.2	87.1	86.5
Passing frequency (passes/h)	**100**	0.0	0.0	0.1	0.1	0.5	0.8	0.9	1.9
	200	0.0	0.0	0.0	0.3	1.2	1.9	2.0	3.3
	300	0.0	0.0	0.0	0.4	1.3	2.2	2.7	5.3
	400	0.0	0.0	0.0	0.1	1.3	2.3	3.1	5.9
	500	0.0	0.0	0.1	0.4	1.5	2.1	2.8	5.4
	600	0.0	0.0	0.1	0.3	1.3	2.0	2.5	6.1
	700	0.0	0.0	0.0	0.3	1.4	2.2	3.0	5.8
	800	0.0	0.0	0.0	0.4	0.9	1.8	2.5	5.4
	900	0.0	0.0	0.0	0.2	1.1	1.9	2.4	4.8
	1000	0.0	0.0	0.1	0.2	1.1	1.4	1.9	4.5
	1100	0.0	0.0	0.0	0.2	0.9	1.0	2.0	3.5
	1200	0.0	0.0	0.0	0.2	0.8	1.5	1.5	3.6
	1300	0.0	0.0	0.1	0.3	0.6	0.7	1.5	3.3
	1400	0.0	0.0	0.1	0.1	0.5	0.8	1.1	2.7
	1500	0.0	0.0	0.0	0.1	0.5	0.7	0.9	2.4
	1600	0.0	0.0	0.0	0.1	0.6	0.6	0.9	2.1

Note: 100 veh/h steps are shown to simplify the table.

Table 2 presents the traffic performance measures from the Aimsun simulation model results. Average travel speed, percent time spent following and passing frequency were evaluated. Percent time spent following and average travel speed showed only normal fluctuations as they are slightly affected by the progressively longer passing lanes, primarily because of the large percentage of no-passing zones of the scenarios (92-98% NPZ). The results are similar to Harwood et al. *(1)*. Passing maneuvers begin to occur when the passing zone length reaches 150 m and passing frequencies increase as the passing zone length increases. The simulation results show similar number of passes than the field data for the same traffic conditions, and slightly lower than Harwood et al *(1)*, who reported a maximum of 2 passes/hour with 300 m passing zone length with 5% of trucks. It should be noted that their conclusions are based on the initial calibration from TAM that was performed with data from the 70's and the vehicles' performance may have changed along these decades. Moreover, their scenarios included 5% of trucks that would increase the percent followers and therefore the demand for passing and number of passing maneuvers.

Overall, the results confirm that passing zones shorter than 200 m do not contribute to the traffic operational efficiency and that they start being efficient from 250 m, for design speed of 100 km/h. They also depended on the directional traffic volume.

The expected number of passes was statistically modeled depending on the passing zone length and the directional traffic volume. Given that passes are nonnegative integer values, the variable was modeled as a Negative Binomial regression model. The assumptions of the model (nonnegative integer values, conditional means not equal to the conditional variances) were fulfilled. The likelihood ratio test indicated that the response variable is over-dispersed. The best fit model is shown in Table 3 and Equation 1. The correlation between the simulations results and the predicted values of the model is 51.6 %, while the McFadden's Pseudo R-Squared is 45.7 %. This can suggest the predictive ability of the model.

Table 3. Summary of the negative binomial regression analysis for passing frequency

Coefficient	Estimate	Standard Error	z value	Prob(>|z|)
(Intercept)	-4.00E+01	7.64E-01	-52.35	<2e-16***
log(Vd)	8.40E-01	5.92E-02	14.19	<2e-16***
log(PZ)	6.18E+00	8.43E-02	73.28	<2e-16***
Vd:PZ	-5.07E-06	2.28E-07	-22.27	<2e-16***
Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1 Null deviance = 34967 on 41346 degrees of freedom Residual deviance = 18982 on 41343 degrees of freedom Theta (Overdispersion parameter) = 0.2205 (Standard error = 0.0036)				

$$NP = {V_d}^{0.84} \cdot PZL^{6.18} \cdot e^{-4.00-5.07E-6 \cdot V_d \cdot PZL} \qquad \text{Equation 1}$$

Where:

- *NP* is the estimated average number of passing maneuvers (passes/h).
- *Vd* is the directional traffic volume (veh/h).
- *PZL* is the passing zone length (m).

Figure 2 shows the expected number of passes depending on passing zone length and traffic volume, applying Equation 1. The number of passes increases as the passing zone length increases. No passes are expected for passing zones shorter than 200 m. From 250 m, the passing zone starts being efficient, and the highest variation on the number of passes is around 400 m. The results also depended on the traffic volume: an optimum traffic volume maximized the number of passes and, from that value, the number of passes decreased as the gaps on the opposing stream are shorter. The highest number of passes was expected for traffic volumes between 300 and 600 veh/h, similar to the results from Moreno et al *(10)*.

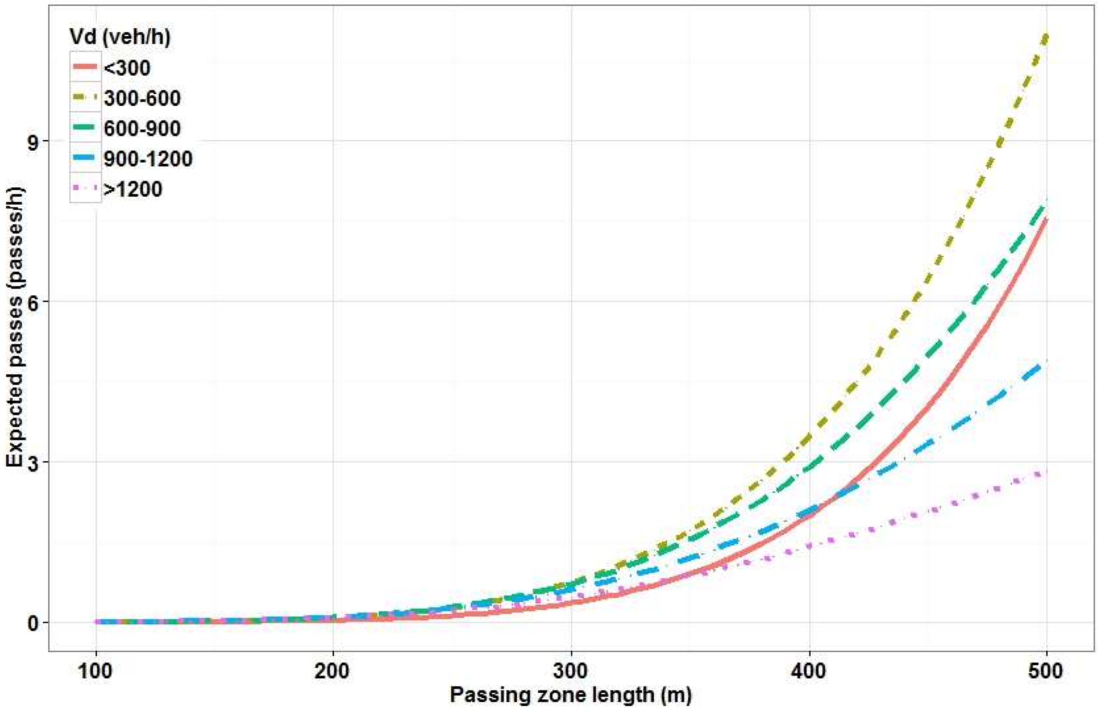

Figure 2. Expected number of passes depending on passing zone length and traffic volume

ANALYSIS OF NO-PASSING ZONES VIOLATION

The second part of the study summarizes the results from the reliability analysis by Llorca et al. *(24)*. The target of reliability analysis is to determine if the probability that a design element is within the acceptable limits (i.e. passing zone length (*PZL*) is higher than the required passing distance (*PD*). Therefore, the performance function is the difference between the system supply and the system demand (Equation 2). The probability of non-compliance is the probability of the demand exceeding the supply (Equation 3).

$$G = PZL - PD \quad \text{Equation 2}$$

$$Pnc = P\,(G < 0) = \int_{G(X)<0} f(x)dx \quad \text{Equation 3}$$

Where:

- *PZL* is the passing zone length (m).
- *PD* is the required passing distance (m).
- *Pnc* is the probability of non-compliance.
- *f(x)* is the density function of *G*.

The required passing distance was modelized using field data. It was a function of impeding vehicle speed, passing and impeding vehicle length, acceleration rate, etc., assuming that the passing vehicle accelerates with constant rate during the entire passing time. The parameters' distributions were used instead of only conservative percentiles. The integral of Equation 3 was solved using Monte Carlo Simulation and First Order Reliability Method. The results provided the probability of non-compliance of the range of passing zone lengths simulated before (Figure 3).

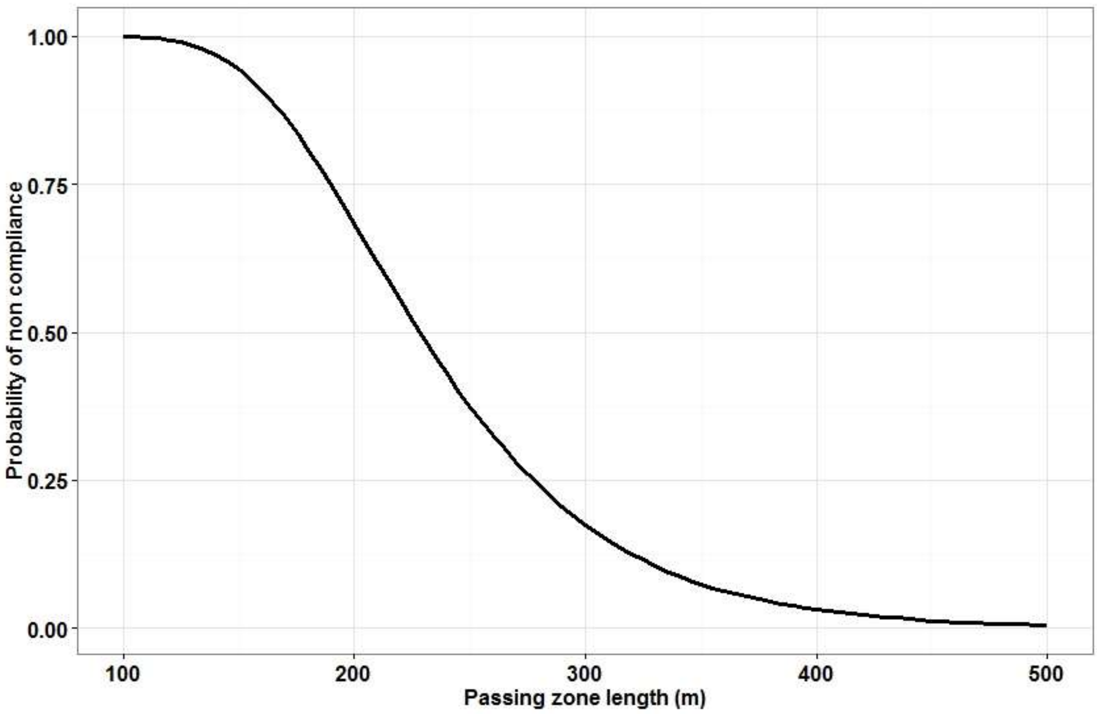

Figure 3. Probability of non-compliance depending on passing zone length

This probability corresponds to the probability that a passing maneuver is longer than the passing zone, and was close to the 100 % for zones under 150 m long and below 5 % over 400 m long. This suggested the risk associated to a certain passing zone length, without considering the expected frequency of passing maneuvers in that passing zone. The complete analysis can be found in Llorca et al *(24)*.

DETERMINATION OF THE MINIMUM PASSING ZONE LENGTH

Establishing the minimum passing zone length should consider both operational and safety effects. To do so, we multiplied the expected number of passing maneuvers and the probability of non-compliance. This new variable quantifies the maneuvers that required a longer passing zone to be completed: the expected number of non-compliant passing maneuvers per hour. This variable can be a potential surrogate safety measure. It should be noted that the non-compliant maneuvers are not associated to collisions between passing and opposing vehicles: they indicate how many maneuvers are completed beyond the marked passing zone.

The value depends on both passing zone length and traffic volume (Figure 4). The number of non-compliant maneuvers is higher for medium traffic flows (between 300 and 900 veh/h) because of the higher number of passing maneuvers. On the other hand, increasing the length of the short passing zones is not always positive. This initial hypothesis (lengthen the passing zone would be safer) can be rejected if minimum passing zone length standard was under 250-300 m.

A maximum number of non-compliant maneuvers can be observed. The maximum depended on the traffic volume and was between 275 m (high traffic volume) and 350 m (low traffic volume). Therefore, the minimum passing zone length should be increased to a minimum of 275-350 m, depending on the traffic volume.

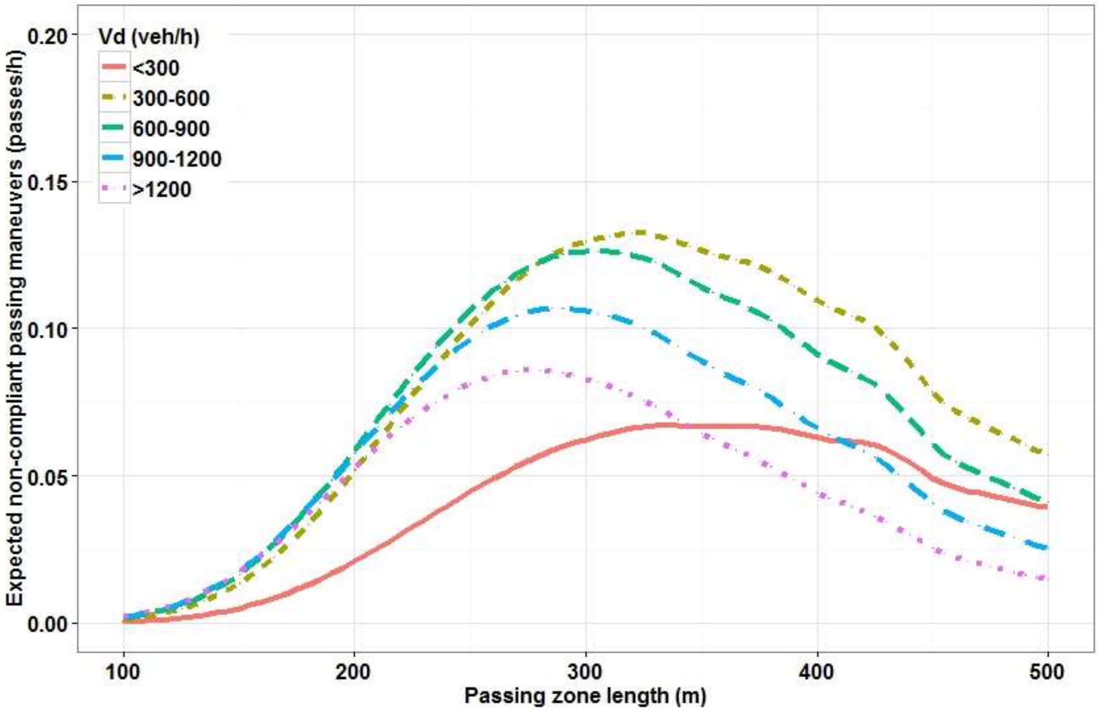

Figure 4. Expected number of non-compliant passing maneuvers depending on passing zone length and traffic volume

However, those passing zones provided the highest number of maneuvers completed beyond the passing zone. Consequently, this strict minimum passing zone should be increased a little to accommodate more complete passing maneuvers. The exact value must be determined by the practitioner, depending on the range of expected hourly volumes along the road and the level of risk willing to take.

The results indicate that higher traffic volumes do not warrant a longer minimum passing zone than low traffic volumes. This conclusions may seem counter-intuitive because a passing maneuver that goes beyond the minimum passing zone would have a higher likelihood of causing a collision in high traffic volumes than low traffic volumes. This hypothesis is true only if driver's passing decision is the same with and without oncoming vehicles. However, observations indicate that, for the same available gap, passing maneuvers are less frequent when an oncoming vehicle is present. The passing model in Aimsun replicates this behavior and adjust the available sight distance if there is any oncoming vehicle, using the *SDfactor*.

Consequently, the higher likelihood of causing a collision in high traffic volumes, where the majority of passing maneuvers are limited by oncoming traffic, is considered in the defined variable; as exposure influences on the percentage of oncoming-vehicle limited passing maneuvers and reduces accordingly the number of passing maneuvers.

CONCLUSIONS AND RECOMMENDATIONS

The present study evaluated the use and safety of short passing zones on two-lane highways to determine geometric design and marking criteria for minimum passing zone length. The operational contribution of short passing zones was obtained using microsimulation. The Aimsun software was calibrated and validated with microscopic and macroscopic field data from Spanish two-lane highways. More than 44,000 directional scenarios were generated varying the length of the passing zone, traffic volume and replications. The basic scenario replicated the scenarios on which were based the current US design and marking criteria. Only balanced flows were considered, as they were the most common during the observations. On the other hand, a previous reliability analysis was applied to determine the probability that the passing zone length is lower than the required passing distance. This analysis accounts the variability of design parameters. The passing model was developed using 1,750 observed passing maneuvers in Spain.

The main conclusions of the study are:

- Passing zones shorter than 250 m do not contribute to the operational efficiency of two-lane roads.
- The expected number of non-compliant passing maneuvers was defined. This new variable quantifies the number of passes that are completed after the passing zone, depending on the passing zone length and traffic volume. It can be used as surrogate safety measure.
- The expected number of non-compliant passing maneuvers is maximum for passing zones between 275 and 350 m long. One passing zone longer than the current minimum (i.e. 300 m) can produce more non-compliant passing maneuvers than the current minimum (i.e. 240 m).
- Considering a maximum number of non-compliant passing maneuvers, the minimum passing zone could be established based on the traffic volume.

Based on the results of the study, we recommend increasing the minimum lengths of the passing zone indicated in both *Green Book* and *MUTCD* (120-240 m). The minimum passing zone length should be at least 350 m for low traffic volumes, 300 m for medium traffic volumes and 275 m for high traffic volumes; so the new minimum passing zone assures that from that length, the number of completed passes increases. These results are based on 50/50 directional split, 100 km/h design speed and 100% passenger cars. Balanced flows are the most common conditions on the Spanish rural highways. On the other hand, the presence of trucks would increase the number of passing maneuvers and therefore the number of non-compliant passing maneuvers, which may increase little the new minimum passing zone length.

The exact minimum passing zone length would be determined by the practitioner, depending on the expected range of hourly volumes along the road and the level of risk willing to take. For reference, these values could vary between 300 and 400 m, depending on the expected hourly volumes, for 100 km/h design speed and level terrain. Therefore, the methodology and results of the study can be directly applied by researchers and practitioners, for those conditions. Nevertheless, the authors acknowledge that further research is needed to evaluate the impact of terrain type, design speed or directional split. Moreover, alternative scenarios and performance measures to the ones used by Harwood et al. and the authors could be considered.

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