RISK EVALUATION OF PASSING SIGHT DISTANCE STANDARDS BASED ON OBSERVATIONAL DATA

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ABSTRACT
This paper presents an application of reliability analysis for evaluating the risk associated with passing sight distance standards in terms of expected probability of noncompliance.

The calculation of passing sight distance (*PSD*) is required to determine where drivers can safely execute passing maneuvers. Traditional *PSD* standards are based on deterministic, theoretical models, which are calibrated using conservative percentiles values for uncertain design inputs to account for uncertainty. They do not provide information about the risk of deviating from them. Reliability analysis is a technique based on limit state design that accounts for the propagation of variability from input random parameters to the design outputs.

A total of 1,098 passing maneuvers were observed on several two-lane highways in Spain, using two different data collection methodologies: external observations and instrumented vehicle. The most significant factors affecting *PSD* were: impeding vehicle speed, passing vehicle acceleration, and headways between impeding and passing vehicles. A uniform acceleration model described passing vehicle trajectory. The characterized input parameters and the passing model were used to perform a reliability analysis. The results showed the probability of noncompliance in different scenarios, defined as the proportion of cases where the required *PSD* would exceed the available sight distance.

American and Spanish *PSD* standards were evaluated. Geometric design standards presented a probability of noncompliance of about 0.15, while some of the marking standards had probability of noncompliance exceeding 0.85. These standards may be associated with higher risk levels if they were followed by drivers. As well, *PSD* risk levels were not consistent for different design speeds, since they underestimate operating speed at some locations.

INTRODUCTION

Several researchers have noted that existing design guides provide a deterministic approach for design requirements, using conservative percentile values for uncertain design inputs to account for uncertainty. These conservative percentile values are not based on safety leading to designs with unknown safety levels *(1, 2)*. One example of the shortcomings of the deterministic approach can be found in the case of existing guidelines for the required passing sight distance (*PSD*). Passing sight distance is the sight distance required to pass safely a slower vehicle, considering an oncoming vehicle approaching on the opposing lane. The existence of a certain proportion of road length with sufficient *PSD* is necessary to determine the location of passing zones. Passing maneuvers in these zones contribute to increase level of service, as faster vehicles can travel at their own desired speeds without suffering delays.

Passing sight distance depends on many parameters, such as the speeds of the impeding vehicle and the opposing vehicle, as well as the acceleration of the passing vehicle. The knowledge about these parameters is imperfect, since they are stochastic and show a high variability among drivers, traffic conditions or geographical locations. The problem of using the traditional approach, based on the selection of conservative percentiles, is that it may result in the definition of potentially too conservative design standards. As well, the deterministic approach provides no information of the consequences of a deviation from the *PSD* design standards.

An alternative approach to account for uncertainty in the geometric design process is reliability analysis. This approach is based on the limit state design procedure, used frequently in structural engineering. This approach accounts the variability of design parameters, considering them as stochastic variables defined by their probability distributions rather than single values. In this approach, the system is considered to fail when the demand exceeds the supply.

Previous studies have analyzed risk levels of road design standards using reliability analysis. In most cases, limit state functions were based on the guideline models, such as stopping sight distance models *(1,3)*.

This paper deals with the use of reliability analysis to evaluate passing sight distance standards. The main elements of the paper are first, the formulation of a limit state function to evaluate passing sight distance based on experimental observation of passing maneuvers on two-lane rural roads, and second, the characterization of input variables from observational data.

PREVIOUS WORK

Passing sight distance

The use of *PSD* criteria in the design stage is required mainly to ensure a minimum percentage of road length having sufficient passing sight distance. On the other hand, in the operation stage, *PSD* marking criteria are used to determine where passing and no-passing zones are established.

Table 1 provides *PSD* geometric design and marking standards for the US and Spain. Generally, the values from Table 1 come from deterministic approaches, where safety risk has not been taken into account and conservative percentiles of variables have been selected.

The previous US AASHTO *PSD* criterion *(6)* used an empirical model where passing sight distance was equal to the sum of four components. *PSD* included the whole distance traveled by the passing vehicle from the initial decision to pass as well as the distance travelled by the opposing vehicle. The current US *PSD* geometric design standard *(5)* is the same as the marking standard provided by MUTCD *(8)* based on research work of Harwood et al. *(9).* These studies adapted MUTCD *PSD* values also for the design criterion. This was also supported on previous analytical *PSD* models *(10-12)* which represented the passing sight distance required to complete the maneuver starting at the critical position.

Spanish geometric design and marking criteria *(4)* were based on analytical models of the maneuver, although no information about the model assumptions and input parameters is provided in the guidelines.

Reliability analysis

The variability observed in standard *PSD* values was also found in research studies. Previous research work have collected data of passing maneuver under naturalistic conditions, in order to compare the existing standards with the observed behavior or to analyze other factors involved in the passing process. Recently, some studies have recorded passing maneuvers from external positions *(13,14)* as well as from instrumented vehicles *(15,16*). Some of these observations showed that existing design criteria, such as the US previous AASHTO standard could be too conservative. The high dispersion in all previous work suggested that the passing process presents a high variability, related to geometric, behavioral or geographical factors. An alternative approach to account for this variability is the use of reliability analysis to analyze and formulate design standards.

There have been several studies using reliability analysis in road design to evaluate the probability of collision at railway crossings *(17),* sight distance limitations *(3,18,19),* traffic signal timing and intersection sight distance *(20-22).* Ismail and Sayed *(1,2)* defined a framework for calibrating crest curves design standards. Ibrahim and Sayed *(23)* established a link between the reliability index and collision frequency in horizontal curves, showing that probability of noncompliance had a significant effect on safety performance function.

In particular, there have been only few applications of reliability analysis to the study of passing maneuver. El Khoury and Hobeika *(24,25)* proposed a probabilistic approach to evaluate risk index of AASHTO *(6)* and MUTCD *(8) PSD* design and marking standards. These studies used a deterministic model *(10)* but they incorporated probability distributions for each input variable. The model was applied to a single case using a Monte Carlo simulation to estimate the risk level of each *PSD* value. El-Bassiouni and Sayed *(26)* evaluated risk of the AASHTO *(6)* design standards. A 20 driver driving simulator experiment was used to calibrate the AASHTO passing maneuver model. This study concluded that the previous AASHTO standard had a probability of noncompliance of 18.7% at the design speed of 100 km/h.

Those studies have not been based on actual field passing maneuver observations, neither to characterize the input parameters nor to verify passing model assumptions. They used probabilistic distributions of input parameters based on a literature review or on a driving simulator experiment, so the validity of results could be limited.

OBJECTIVES

The main goal of this study is the evaluation of the risk levels of passing sight distance design and marking criteria using reliability analysis based on experimental data. The specific objectives are:

- Formulation of a limit-state function for passing maneuver by modeling observational data.
- Statistical characterization of input variables.
- Reliability analysis of passing maneuver at the selected scenarios.
- Evaluation of existing *PSD* criteria.
- A procedure to obtain *PSD* design criteria from a risk-based approach.

METHODOLOGY

Data collection

The main contribution of this study was the characterization of the performance function and their input parameters from observational data. Data collection has been based on video recording of passing maneuvers under naturalistic conditions, which minimizes the influence of observers. Two methodologies have been used to record passing maneuvers *(14,16)*.

The first methodology (static) consisted of video recordings from external fixed positions. Data was collected in 20 passing zones located in 10 two-lane rural highways segments in the surroundings of Valencia (Spain). The mobile traffic laboratory of the Universitat Politècnica de València (Spain) has six surveillance digital video cameras installed on the top of an elevator platform. Zoom and focus of the cameras were adjusted on site to collect video images of entire passing zones with uniform quality (Figure 1a). A total of 648 maneuvers were recorded in 20 passing zones. In 120 maneuvers, the speeds of impeding vehicles were characterized extracting their trajectory from video data. In the same locations, the speed of 450 vehicles in free-flow conditions was measured either from video data or with a LTI T100/T200 laser speed sensor.

The second methodology (dynamic) was based on an instrumented vehicle, which was driven along various road segments, which included passing zones observed with the first method. The objective was for other vehicles to pass the instrumented vehicle, collecting data of these maneuvers and the entire following process (Figure1b). The instrumented vehicle was equipped with four 720x576 pixels resolution cameras, covering rear, left side and front of the vehicle, and connected to a Racelogic VBOX recording unit, as well as with a high definition mini-camera covering rear part. Two LTI True Sense S200 laser rangefinders were installed to measure headways between vehicles behind and in front of it. Accuracy of the distance measurement was 4 cm. Measuring systems are very small and are installed inside the car (cameras and recording units) or in front and rear bumpers (rangefinders). A 10 Hz GPS tracker registered the position and speed of the vehicle. Instrumented vehicle speed was selected thanks to the observations of the static methodology, which had been previously carried out. This speed was around the 15th percentile of speed of impeding vehicles at this location, neither too fast nor too slow, balancing a realistic behavior and a high sample size. No unexpected maneuvers of drivers who follow the instrumented vehicle were observed, such as following without pass or with longer headways.

The instrumented vehicle data provided an accurate characterization of 450 passing vehicle trajectories. They were observed in 8 two-lane highway segments in the surroundings of Valencia (Spain). A homogeneous sample of 150 maneuvers was selected to characterize the passing vehicle trajectory. This sub-sample included simple maneuvers (only one impeding vehicle) performed by light vehicles (a passenger car or van). Using a combination of video, GPS and laser rangefinder data, following variables were measured (Figure 2):

- Starting time of passing maneuver: $t1$
- Abreast position time: $t2$
- Ending time of passing maneuver: $t3$
- Crossing time between opposing and passing vehicle: $t4$
- Headways at the start $h(t1)$ and end $h(t3)$ of passing maneuver.
- Speed of impeding vehicle: Vi
- Speed of passing vehicle at the start of the passing maneuver $Vp(t1)$ and at the end $Vp(t3)$

The length of passing and impeding vehicle *Li* and *Lp* were obtained after identifying its brand and model. The selection of the previous variables followed previous research studies (9-15). These variables provided information about passing duration, passing speeds and distance traveled during passing. These are components of *PSD*. Table 2 presents the fundamental statistics of the observed and analyzed data.

Reliability theory

Reliability theory provides the analytical tools for accounting for variability of input parameters throughout the design process. The main target of reliability analysis is to determine the probability that a design element (the available sight distance, *ASD*) is within acceptable limits (the required passing sight distance, *PSD*).

The probability of failure is adopted as an indicator in several civil engineering disciplines. However, according to Ismail and Sayed *(1),* the term probability of noncompliance (P_{nc}) is more appropriate for road safety applications, since there is not any physical failure in those systems.

The reliability analysis is based on a performance function *G(X),* where *X* is a *N*-dimensional vector of input parameters *X= x1, x2,…,xn*. The performance function is defined such that it is positive for favorable system conditions. It is commonly written in terms of supply *R* and demand *S* (Equation 1). Therefore, if demand exceeds supply the function is negative and the system failure is produced.

$$G(X) = R(X) - S(X) \tag{1}$$

In highway geometric design, the supply term is the provision of safe and comfortable driving conditions, such as available sight distance. On the other hand, demand depends on driver or vehicle requirements, such as stopping sight distance or passing sight distance. Randomness of the performance function is characterized by their probability density function *f(x).* Equation 2 gives the probability of noncompliance of the system.

$$Pnc = P\,(G < 0) = \int_{G(X)<0} f(x)dx \tag{2}$$

The integral in equation 2 can be solved by numerical or analytical methods. Numerical methods are based on Monte Carlo simulation. This method starts with the generation of n-dimensional random vectors according to the normal probability function, which are transformed to the input parameter distributions in order to evaluate the performance function *G(X).* Probability of noncompliance is the proportion of negative *G(X)* cases of the total number of cases.

On the other hand, analytical analyses are based on different approximations of the performance function. First order second moment reliability method (FOSM) is based on the first-order Taylor expansion of the performance function at the mean values of the design inputs. First order reliability method (FORM) is based on the same first-order expansion but performed at the design point, so that non-normal input variables can be considered. The objective of the FORM method is the finding of the design point where function *G(X)* is equal to zero. Highly nonlinear performance functions need to be solved using second order reliability methods (SORM), although this method is seldom needed in road safety applications *(1)*. This study used FORM method, although some cases were solved using Monte Carlo simulation, for comparison purposes.

The Performance function

The limit state function (or performance function) of equation 3, was formulated as the difference between the system supply and the system demand, according to the reliability theory. In this case, the supply term was the available sight distance at a specific location (*ASD*), provided by road geometry. The demand was the required distance to complete a passing maneuver (*PSD*).

$$G = ASD - PSD \quad (3)$$

For this analysis, the supply term *ASD* was selected as a constant depending on each analysis scenario. This facilitate the application of resulting *PSD* standards to *ASD* profiles obtained in reality. This *ASD* profiles may account not only for specific geometric elements (such as vertical or horizontal curves) but also for any type of sight distance obstruction. Analysis scenarios considered a wide range of *ASD* values (from 200 to 1100 m), which represented the majority of values measured in the data collection sites. On the other hand, the demand component was calculated as a function of the parameters which had a significant influence on *PSD*, according to the calibrated model.

PSD model

According to its definition, passing sight distance is the sum of three components, as shown in equation 4.

$$PSD = d13(passing) + d13(opposing) + d34(safety\ margin) \quad (4)$$

The first component is equal to the distance traveled by the passing vehicle on the left lane. The distance *d13(passing)*, as well as the required time *t3-t1* were calculated using a uniform acceleration model. According to this, passing vehicle accelerates with a uniform rate during the entire left lane occupation time.

This model was selected among a variety of assumptions in the literature, such as uniform speed *(6),* or uniform speed from critical point *(10,11).* Alternative models were also evaluated, such as acceleration linear functions of time or speed. The model was calibrated using the instrumented vehicle data. The calibration consisted in minimizing the square error between the estimated and the observed value of the following variables, for each individual maneuver:

- distance travelled during the entire passing maneuver *d13 (passing)*, in *t3-t1* (m)
- distance travelled until the abreast position: *d12(passing)*, in *t2-t1* (m)
- initial speed *Vp(t1)* (m/s)
- final speed *Vp(t3)* (m/s)

The results of the acceleration model calibration showed that the root mean square error of the previous four variables was under 6% of their means. This model balanced low error (compared to uniform speed, with root mean square errors up to 13%) and model simplicity (compared to uniform speed form critical point model).

The second component of passing sight distance *d13(opposing)* was assumed to be a uniform movement of opposing vehicle during passing time, and the third component *d34(safety)* was calculated as the sum of distances travelled at uniform speed by the passing and the opposing vehicle during a critical safety margin. Equations 5 to 8 were used to calculate the components of *PSD*.

$$t3 - t1 = \frac{-\left(V_p(t1) - V_i\right) + \sqrt{\left(V_p(t1) - V_i\right)^2 + 2a\left(L_i + L_p + h(t1) + h(t3)\right)}}{a} \quad (5)$$

$$d13\ (passing) = V_p(t1) \cdot (1-\alpha) \cdot (t3-t1) + \frac{1}{2} a \cdot (t3-t1)^2 \cdot (1-\alpha^2) \quad (6)$$

$$d13\ (opposing) = Vo \cdot (1-\alpha) \cdot (t3-t1) \quad (7)$$

$$d34\ (\text{safety margin}) = (t4-t3)_{critical} \cdot (Vo + Vp(t3)) \quad (8)$$

where:

- *Vp(t1):* initial passing vehicle speed (m/s)
- *Vi*: impeding vehicle speed (m/s)
- a: acceleration rate (m/s^2)
- *Li* and *Lp*: length of impeding and passing vehicles (m)
- *h(t1)* and *h(t3)*: headway impeding-passing vehicle at *t1* and *t3* (m)
- α: proportion of passing time at the analysis point
- *Vo*: opposing vehicle speed (m/s)
- $(t4\text{-}t3)_{critical}$: time between end of passing maneuver and crossing with the opposing vehicle (s)
- *Vp(t3)*: final passing vehicle speed, equal to $Vp(t1) + a \cdot (t3-t1)$ (m/s)

Since the required PSD decreases during the maneuver progress (from its maximum at the starting time until zero when it ends), the parameter α was included. It is defined as the proportion of left lane occupation time *t3-t1* at the analysis point. The start of a passing maneuver corresponded to α=0 (as passing has not yet started), while the critical point was assumed at α=0.5. A value of α=1would mean that the maneuver is already completed. The assumption of critical point at α=0.5 was similar to other models *(10,11),* and was necessary since the observation of aborted maneuvers was very unusual (observed 3 aborted and 1,098 completed).

Input Parameters

The speeds of both impeding and opposing vehicle were obtained from static observations. The opposing vehicle speed was assumed to be equal to the free-flow operating speed because opposing vehicles drive in this condition. The speeds came from a normal distribution, at the 95% confidence level (Chi-square test) and were different for each design speed level.

Average vehicle lengths from a previous study *(14)* were assigned to each vehicle category to obtain the lengths distribution. The analysis considered both heavy and light impeding vehicles, but only light passing vehicles, according to observations.

Table 3 shows the *PSD* model parameters. Distribution fitting was significant at the 95% confidence level according to Chi-Square tests.

The safety margin, or clearance time, was estimated from instrumented vehicle collected data. However, experimental data provided only the time between the end of passing maneuver and the crossing with the next opposing vehicle, named previously *t4-t3*. This time should not be identified with the critical safety margin since it includes many different situations, including both forced and not forced passing maneuvers. In consequence, their distribution include very high values which are not reflecting the critical value necessary to estimate a minimum *PSD* requirement. Based on the agreement found on previous research on passing maneuver *(9-11)*, a critical value of 1 second is recommended. This value was chosen also since it is low percentile of a 160-maneuvers sub-sample of observed *t4-t3,* ranging between 0.8 and 20.0 s. In this case, the use of a statistical distribution was discarded, because it would have caused the existence of negative (i.e. with normal distribution) or very small values (i.e. with lognormal), which are not realistic.

After the individual characterization of passing variables, a statistical analysis was done to analyze possible correlations among the previously defined variables. Correlation coefficients were under 0.4, and consequently, they were not included in the analysis.

ANALYSIS AND RESULTS

In this study, first-order reliability method (FORM) has been used, since most of the input variables do not follow a normal distribution and the design model is nonlinear. However, to verify the adequacy of FORM method, it was compared with Monte Carlo simulation. Sampling analysis does not make any linearization of the performance function. Therefore, if significant differences were found between sampling and FORM analysis, the linear expansion of the performance made by the FORM method would not be valid.

The Monte Carlo sampling analysis was performed in a part of analysis scenarios: design speed equal to 100 km/h and different *ASD* and impeding vehicle types. A 2% target coefficient of variation of the probability of noncompliance was reached in less than 100000 samples. Results of FORM and Montecarlo analyses were compared. The results were very similar (85% of cases with differences under 5% in the probability of noncompliance and 60% under 1%). This can support the FORM linear approximation around the design point. This conclusion is similar to other studies, which applied FORM analysis to similar reliability problems *(1,26)*.

In order to compare and review the different existing *PSD* criteria, different scenarios have been analyzed. The selection of different analysis conditions covered the whole range of situations where data was collected as well as where existing *PSD* standards can be applied. As a result, a total of 4 design speeds (from 60 to 120 km/h), 10 available sight distances (from 200 to 1100), 2 types of impeding vehicle (heavy and light vehicles) and 2 positions in the passing maneuver (α=0 – start and to α=0.5 – critical position) have been analyzed.

As shown in Figure 3, P_{nc} increases with higher design speeds, given a fixed sight distance (*ASD*). On the other hand, P_{nc} decreased when available sight distance (*ASD*) increased, since longer available sight distances are associated with safer conditions. Between 300 and 700 m *ASD*, probability of noncompliance decreased faster, so any variation of *ASD* lead to a significant decrease in P_{nc}. If the impeding vehicle was a heavy vehicle the probability of noncompliance was higher, due to the difference in length.

In FORM analysis, importance vectors are intended to reveal the relative importance of input parameters. The *Alpha-vector* is an importance vector for input random variables. The higher the absolute value of its components $alpha_i$, the more important random variable *i* is. The results showed that the variables with a higher influence on the value of the probability of noncompliance were the acceleration and initial speed of passing vehicle, as well as the headway *h(t3)* at the end of the maneuver.

PSD standards risk evaluation

The reliability analysis has been applied to all of the selected scenarios, in order to provide a risk measure of different *PSD* standards. Risk has been characterized by the value of the P_{nc}. The higher the P_{nc}, the higher the potential risk drivers should expect if they followed the standard. It should be noted that data was collected at different locations in Spain. Therefore, the comparison with US standards should be considered with caution, as US criteria were never applied on the observed roads.

Reference speed of each *PSD* standard was either the design speed (*Vd*) or the 85th percentile of operating speed (*V85*) at the observed locations.

Figure 4a represents the probability of noncompliance of different US and Spain existing design and marking criteria. These standards are based in the *PSD* at the starting point of a passing maneuver.

Figure 4b shows the probability of noncompliance of the criteria based in the required *PSD* at the critical point. This is the case of the current AASHTO design standard (5), as well as the equivalent MUTCD (8) and the Spanish marking standard (7) used to establish the end of passing zones.

There are significant differences among different *PSD* standards, as well as different design and operating speeds. Generally, design criteria had a lower P_{nc}, especially at design speeds over 90km/h (corresponding to 85th percentiles of operating speeds over 110 km/h).

Although current AASHTO and MUTCD criteria use the same passing maneuver model, they provided different results since they are applied using design and operating speed, respectively. Operating speed-based standards showed a lower probability of noncompliance. Generally, the use of 85th percentile of operating speed determines a more consistent risk level (the same risk at different speeds). The reason is that design speed usually underestimates the operating speed, especially at lower design speed segments which have long tangent sections where passing is permitted.

On the other hand, Spanish marking standard (8.2 IC) showed the higher probability of noncompliance, either at starting of passing maneuver or at the critical point. This may be associated with a high-risk level if drivers followed the standard. However, a more common consequence is that drivers do not pass other vehicles where available sight distance is close to the standard requirement.

Framework for new PSD standards

The objective of this section is not to determine a new *PSD* criteria (since it would require a more extensive data collection including crash data, as well construction or accident-related costs). A procedure to formulate *PSD* standards based on reliability analysis would have the following steps:

1. Selection of a target probability of noncompliance (P_{nc}). In this case, 5% and 15% were chosen for demonstration, in order to provide a guideline on how to address the *PSD* standard formulation.
2. Selection of an operating speed, either measured (for existing roads) or estimated (for new roads, based on estimation models (*27*)). The use of design speed should be avoided, because it may underestimate operating speed on longer tangents. The reason of this is that design speed is taken from the minimum horizontal curve radii (or vertical curve curvature rate), which does not reproduce the speed on long tangents where passing zones are located. Moreover, speed limit does not estimate adequately the operating speed of vehicles in long sections, as measured in the data collection.
3. Selection of the required *PSD* based on reliability analysis results (Figure 4). The application of the 5% and 15% P_{nc} levels to different operating speeds is shown in Figure 5.

The solid lines in Figure 5a show the values of required *PSD* at the starting point of the maneuver, determined from Figure 4a. They indicate the starting point of the passing zone (where *ASD* exceeds that *PSD*). If these standards were used to determine the end of the passing zone, they would be very conservative, since no left lane occupation is permitted after this point, according to most international driving regulations.

In contrast, the dashed lines in Figure 5a show the sight distance necessary to start a no-passing zone (they were obtained from Figure 4b). This approach less conservative but still safe, since there is a buffer area where drivers can complete the maneuver safely but not legally. In addition, the length of passing zones should be, at least, the distance traveled on left lane by passing vehicle. This distance (shown in Figure 5b) has been calculated from equation 6, using the same model that in the reliability analysis. The input parameters vector *X* at the point where

G(X)=0 was used. Those values provided the *d13* value, which was consistent with the selected probability of noncompliance.

It should be noted that in Figure 5, only light impeding vehicles were considered. Finally, there is not any reason to use different standards for geometric design and marking. The adequacy of these standards to each location would depend on the quality of both sight distance and operating speed accuracy, on either the design or the operation phase.

CONCLUSIONS

This study developed a reliability analysis on passing sight distance, based on observation of maneuvers in a sample of Spanish two-lane roads. The application of this tool to the evaluation of passing sight distance may account for existing variability and for the risk of deviating from design and marking standards. Although previous work (24-26) have already performed reliability analyses for this application, input parameters were not characterized from real data.

The main methodological conclusions of this paper are as follows:

1. Observation of 1,098 passing maneuvers in two-lane rural roads in Spain using two recently developed methodologies.
2. Calibration of a model to describe passing vehicle trajectory on the opposing lane, based on field data. Characterization of input parameters by their statistical distributions.
3. Formulation of a performance function based on observational data.
4. Reliability analysis at different scenarios: design speeds from 60 to 120 km/h and available sight distances from 200 to 1100 m.

This method was applied to estimate the risk level (in terms of probability of noncompliance) of Spanish geometric design and marking standards. The results of this analysis were:

1. The current Spanish design standard showed relatively low probability of noncompliance (between 0.15 and 0.30).
2. The Spanish marking standards had a higher probability of noncompliance (over 0.85 at lower design speeds).
3. Generally, standards did not present consistent levels of probabilities of noncompliance among different speeds. They show higher risk level at low design speed. The reason of this may be related to the inaccurate estimation of operating speed by design speed, especially at locations with lower design speeds.
4. Consequently, marking standards might be associated with risky situations if drivers followed them. On the other hand, design standard might be conservative, since the expected probability of noncompliance was 0.15 at high design speeds.

As a result, a consistent risk-based approach for PSD standards was developed. This approach starts with the selection of a target probability of noncompliance. The estimation or measurement of input parameters at a specific location (such as operating speed and impeding vehicle length and speed) is used to estimate the required PSD that satisfies the target probability of noncompliance. Therefore, uniform risk levels may be expected at every location.

Further work is needed in order to establish a link between the probabilities of noncompliance, and other safety measures, such as crash data or traffic conflicts. This will be necessary to determine the most adequate values of the target probability of noncompliance, in order to develop reliable risk-based standards.

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LIST OF TABLES AND FIGURES

Country - Standard		*PSD*(m) at reference speed (km/h)									Reference Speed
		40	50	60	70	80	90	100	110	120	
Spain 3.1 IC (2000) *(4)*		200	300	400	450	500	550	600			*Vd*
US AASHTO Green Book (2011) *(5)*		140	160	180	210	245	280	320	355	395	*Vd*
US AASHTO Green Book (2001) *(6)*		266	341	407	482	538	613	670	727	774	*Vd*
Spain 8.2 IC (1987) *(7)*	Start of passing zone (a)	145	180	225	265	310	355	395			*VM*
	End of passing zone (b)	50	75	100	130	165	205	250			*VM*
	Minimum passing zone length (c)	160	200	245	290	340	385	435			*VM*
US MUTCD (2003) *(8)*		140	160	180	210	245	280	320	355	395	*V85*
Vd: design speed, *VM*: posted speed limit, *V85*: 85th percentile of operating speed											

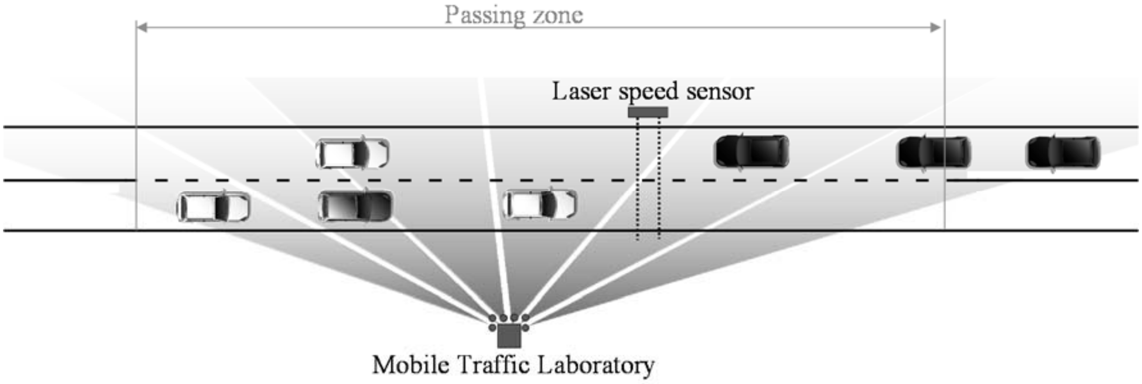
Table 1. PSD design and marking standards

Variable	Units	Sample size	Minimum	Mean	SD	Maximum
d12(passing)	(m)	150	39.2	61.2	19.0	98.0
d13(passing)	(m)	150	114.1	163.8	42.0	241.6
t2-t1	(s)	150	1.7	2.9	0.9	4.6
t3-t1	(s)	150	4.8	7.1	1.8	10.1
h(t1)	(m)	150	3.4	7.5	3.7	13.5
Vp(t1)	(km/h)	150	58.6	71.1	10.4	89.3
h(t3)	(m)	150	10.0	21.1	8.2	35.7
Vp(t3)	(km/h)	150	73.0	88.8	11.1	109.2
Vi (dynamic method)	(km/h)	150	55.7	65.5	8.3	78.0
Vi (static method)	(km/h)	120	42.8	77.3	18.9	109.8
free-flow speed	(km/h)	450	63.0	90.1	18.0	120.1

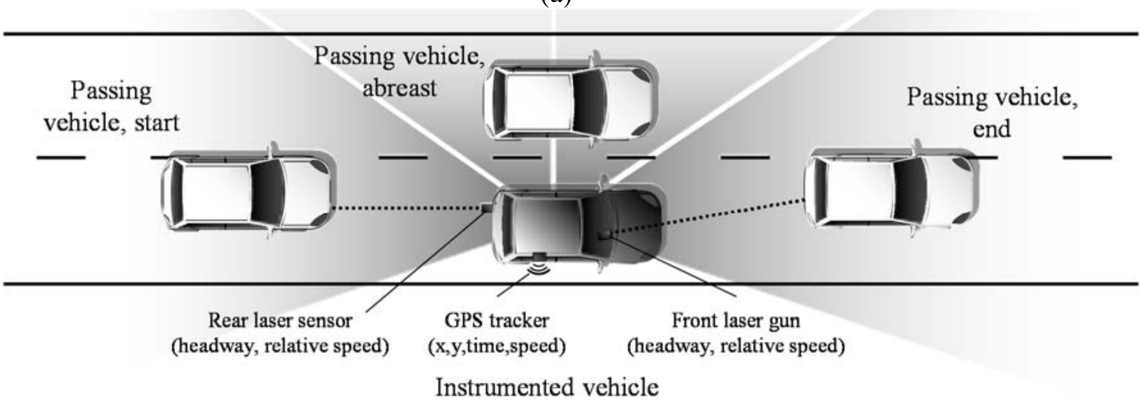
Table 2. Summary of data collection variables

Variable	Code	Units	distribution	mean	SD
Passing vehicle relative initial speed	*Vp(t1)/Vi*	-	lognormal	1.10	0.05
Acceleration rate	*a*	m/s^2	lognormal	0.77	0.47
Headway passing-impeding at start	*h(t1)*	m	lognormal	9.61	5.65
Headway passing-impeding at end	*h(t3)*	m	lognormal	23.88	9.58

Table 3. Passing vehicle acceleration model variables



(a)



(b)

Figure 1. Data collection methodologies: (a) static and (b) dynamic

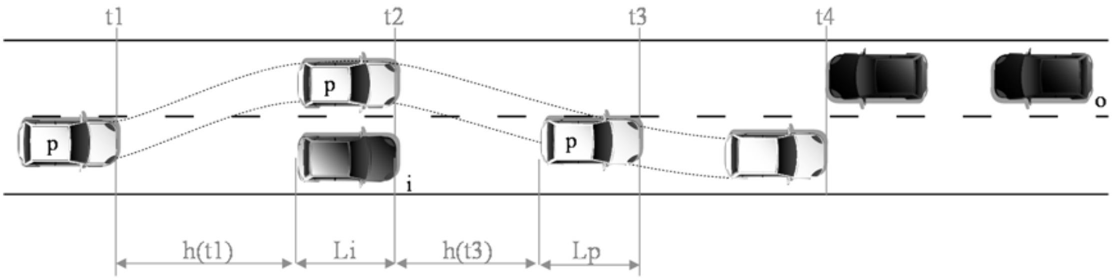
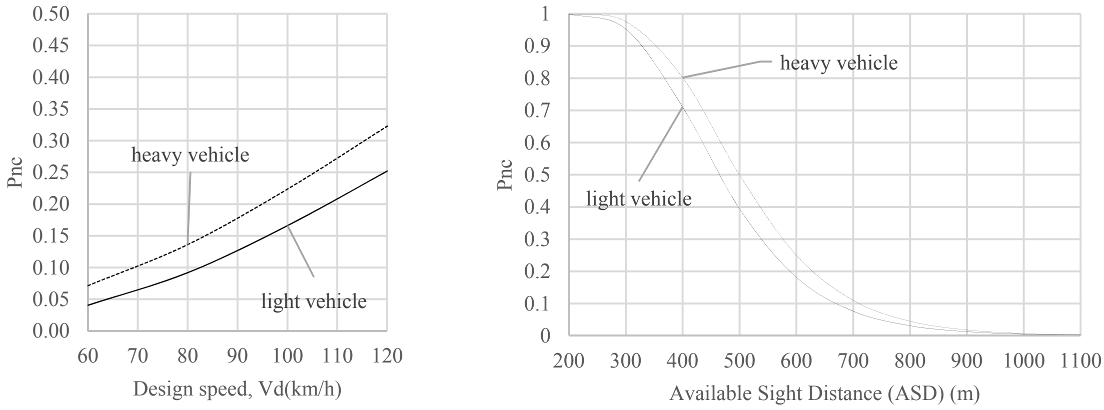


Figure 2. Passing maneuver dynamic variables



(a) (b)

Figure 3. Vd, ASD and impeding vehicle type effect on P_{nc}

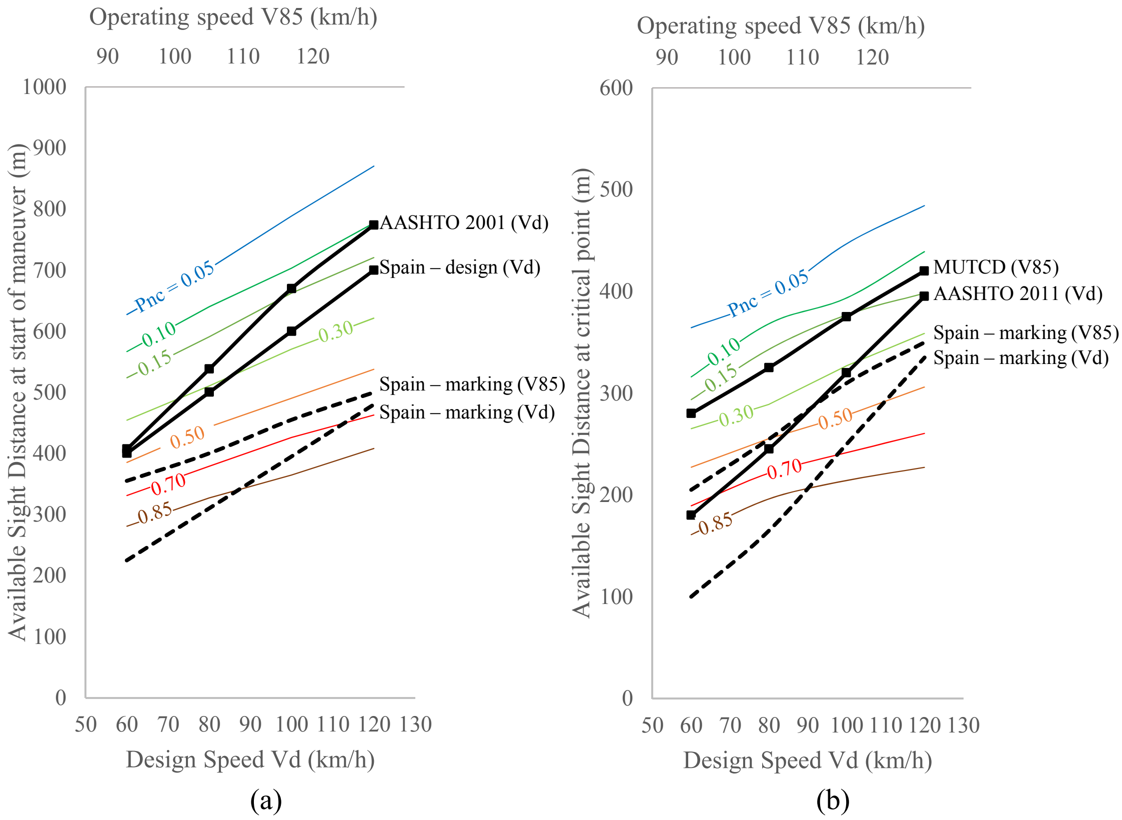
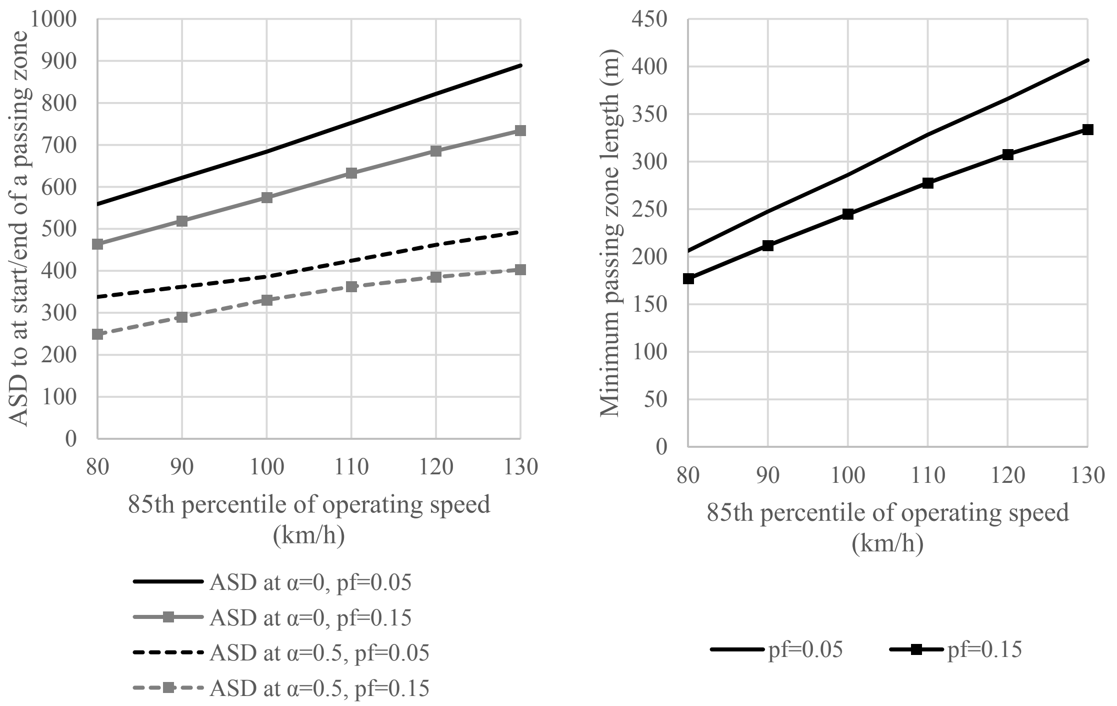


Figure 4. P_{nc} of existing criteria: (a) at the starting point and (b) at the critical point



(a) (b)

Figure 5. Sight distance requirement at start and end of passing zones. Minimum passing zone length requirements.