EVALUATION OF PASSING PROCESS ON TWO-LANE RURAL HIGHWAYS IN SPAIN USING A NEW METHODOLOGY BASED ON VIDEO DATA

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ABSTRACT

Drivers need enough Passing sight distance (PSD) to pass slower vehicles with safety. This can help to improve traffic operation on two-way two-lane highways. Existing models propose different values of PSD, according to different assumptions. Only in some cases these models were based on field data of passing maneuvers.

This research proposes the design of a new methodology to observe passing maneuvers on existing highways with help of 6 video cameras installed on a fix point next to passing sections. The use of a larger number of cameras allows the complete registration of trajectories along the entire passing zone, with uniform image resolution. The methodology was applied to register a sample of 234 maneuvers on 4 passing zones. Trajectories of 58 of them were completely described and analyzed using specific restitution software.

Results are compared with existing PSD models. AASHTO model proposed distances travelled on the left lane are similar to average observed distances if the passed vehicle is one truck, and between 50 and 100 m higher if one passenger car is passed. Higher differences, over 100 m, were found between measured data and PSD model of Hassan et al., especially at high design speeds. Observed average speed difference between passing and impeding vehicles is significantly higher than in all models.

Variables with strongest influence on the time and distance travelled on the opposing lane are: type and speed of the passed vehicle and the length of the passing zone. Left lane time and distance increase with this length.

BACKGROUND

Passing on two-way two-lane highways is one of the most important maneuvers for the operation of traffic on these roads. Passing allows drivers of faster vehicles to drive at their own desired speed and to avoid interferences with slower vehicles that cause delays.

Rural two-lane highways represent still the longest part of the highway networks. Despite of traffic volume on these highways is lower than on motorways, accident rates are significantly higher (1).

Passing-related accidents are especially serious, because of the existence of up to three vehicles at high speeds (the passing, the impeding and the opposing vehicle), with opposing paths on the road. However, it is very difficult to identify the real causes of one accident, in order to associate it with the passing maneuver. Recent studies with these objectives are not common.

Driving safety analysis by means of traffic conflict techniques (TCT) could reinforce the study of passing-related accidents. However, there is not any specific conflict indicator defined for the passing maneuver, which could consider the particular problems of passing. Only some few research studies (2) have used the "Time to Collision (TTC)" as conflict indicator, despite it is usually used to analyze crossing safety.

Consequently, highways are designed and signed using criteria based on Passing Sight Distance (PSD). PSD must be seen by one driver along the opposing lane in order to pass a slower vehicle when a third opposing one is approaching.

PSD used in geometric design and marking criteria could be calculated with a large number of different PSD models. Dispersion in results of those PSD models is very high (3).

US design criteria for two-way two-lane highways are presented in AASHTO Green Book of 2004 (4). The last revision of this model was made in 1994. PSD components were calibrated with field data of passing maneuvers from different research between 1938 and 1958.

PSD of AASHTO models begins with a perception-reaction time and ends at the moment of the return to the own lane. Opposing vehicle is considered from the point when passing and passed vehicle are in abreast position. Aborting the maneuver is only considered until this abreast position.

In contrast of PSD model of AASHTO (4), Glennon (5) and Hassan et al. (6) propose analytic models of PSD. These models are based on equations of the movement of the three vehicles.

Glennon and Hassan et al. locate a 'critical position' at the point where sight distances to abort and to complete the maneuver are equal. After this point it is better to complete the pass than to abort. The difference between both authors and AASHTO model is the definition of PSD. Glennon and Hassan only consider the part of sight distance needed from the critical position to the end of the passing, instead the distance from the perception-reaction stage, which is considered by some authors as too conservative. Glennon and Hassan's PSD proposed values are consequently lower.

In addition to those cited PSD model, a higher number of PSD models were formulated. Some analytical deterministic PSD models are presented by Rillet (7), Rocci (8), or Wang and Cartmell (9). More recent are probabilistic models that associate PSD with levels of safety, like El Khoury and Hobeika (10) or El-Bassiouni and Sayed (11).

Clear differences are also found between geometric design and marking criteria employed in different countries. These two criteria are incompatible in all the analyzed cases, like in US (AASHTO Green Book for geometric design and MUTCD for marking (4), (12)) or in Spain (13), (14).

A quite small number of PSD models were based on field studies. Most recent extensive field data was obtained by Polus et al. (15) or Harwood et al. (3). These authors have recorded video from external fixed positions of passing zones. Only one camera was used in each passing zone, and times and distances were measured in video images. Traffic data was also recorded

Polus et al. observed up to 1,500 passing maneuver, but analyzed only a small part of them. Also Harwood analyzed 60 of over 360 maneuvers.

According to authors, some passing maneuvers could not be analyzed because they have started out of the camera field or too far to get accurate distance data. Curvilinear alignments did not allow the necessary accuracy either.

A different methodology was used by Carlson et al. in 2006 (16). Carlson took video data from a moving vehicle inside the traffic flow. The moving vehicle drives at slow speeds as impeding vehicle. Data from Carlson was combined and included in Harwood's study (3).

The final results of Polus et al. and Harwood et al. studies disagree. Polus recommends the AASHTO PSD values, or even higher, if the passed vehicle is a heavy vehicle. In contrast, Harwood considers AASHTO model too conservative because of the existence of the critical position. Harwood et al. recommend using the MUTCD criteria (with assumptions of Glennon's model) as geometric design criteria, instead of AASHTO criteria (17).

OBJECTIVES

High dispersion in criteria, models and field data suggests a new research of passing maneuvers on two-way two-lane highways. Moreover, the need of obtaining more accurate data of passing maneuvers motivates the test of a new methodology.

This research will design a new methodology to obtain data from observed maneuver on rural roads. Methodology must improve data acquisition by analyzing complete trajectories of all vehicles that participate in the passing maneuver.

Once the methodology is designed the second objective is to obtain an extensive database of passing maneuvers. Each maneuver should be described by the complete path of all the participating vehicles on the roads: position, time, speed and acceleration at any time.

After that, the research will analyze statistically the data and propose a revision of the most cited PSD models, and their assumptions, to be applied in Spain.

METHODOLOGY

The methodology of this research is based on video data recording and restitution of trajectories.

The first important advance in relation to past research with similar methodologies is the incorporation of a higher number of video cameras. Up to 6 digital cameras can be installed on a Mobile Traffic Laboratory developed by the Highway Engineering Research Group (HERG) of the Universidad Politécnica de Valencia (Spain), in order to make a description in detail of the complete evolution of vehicles in passing maneuvers.

Mobile Traffic Laboratory is an articulated platform which can be raised up to 12 m high. Cameras are installed on the highest point of the platform. Focus and zoom of these cameras is controlled from a laptop in real time by means of a wireless network.

A large area can be recorded with a correct position and zoom of each camera. Each camera records a smaller area than if only one camera was available. Consequently, video images are obtained for long zones up to 1,000 – 1,500 m when the Mobile Traffic Laboratory is installed in the middle of the passing zone. Video quality is also uniform along the whole zone. A passing maneuver along the six cameras is shown in FIGURE 1 throw different frames.

Starting at distances of 300 m from the position of the Mobile Traffic Laboratory the resolution of cameras restricts the analysis of maneuvers. Trajectory processing is, according to that limitation, possible along up to 600 m of passing zone.

Potential effects over drivers should be reduced by choosing the appropriate position of the platform. The best position should ensure good visibility from the cameras and restricted visibility form drivers to the Moving Traffic Laboratory.

When the equipment is installed next to the highway, the six cameras record video simultaneously. After that video data is processed in order to obtain the trajectories and different characteristics of maneuvers.

Path restitution is based on perspective restitution. Real dimensions of objects are calculated from their representation in the video frame, thanks to geometrical relationships between reality and perspectives. Each video frame is treated as perspective drawing of the reality. Individual restitution of a frame locates the vehicles on their position on the highway at this time. If the process is repeated along all frames, the entire trajectory will be obtained.

This conversion of coordinates is possible after measuring reference polygons on the road, which are observed on videos and match up the road marking. Trajectories of the up to three vehicles are obtained on a two-dimensional coordinate system, which matches up with length and width of the highway. Perspective distortion does not affect the restitution since reference lines which are observed in video data were measured before in the reality, along the entire passing zone.

All the process was made with specific software developed by the HERG of the Universidad Politécnica de Valencia. Several applications of this software have been already presented (18).

Positions of vehicles along the six cameras with a frequency of 5 points per second are combined and the complete trajectory can be calculated. Speed and acceleration profiles of the three vehicles along the maneuver are also calculated. This means that a sample vehicle in a passing maneuver of 10 seconds is described at least by 50 points.

FIELD STUDY

With these methodology a total of 234 maneuvers were observed. 58 passing maneuvers were analyzed with data of trajectories of, at least, the passing and impeding vehicles. Near 25 percent of maneuvers could be analyzed using the described restitution software.

The study took place on four passing zones in the surrounding of Valencia (Spain) in 2010, on two different rural roads. Passing zone length considered was between 245 m and 1,300 m, in order to study the effect of this length in passing maneuvers. These lengths are representative of almost that all existing passing zones in Spanish roads.

Short zones present a higher rate of analyzed maneuver (up to 63%) than long zones (13%) because off focus and resolution problems at 300 m on up.

Operating speed (85^{th} percentile) on the passing zones was between 98 and 120 km/h. These speeds were calculated using the developed software. Free flow and total flow operating speeds were separately obtained.

Only day light passing maneuvers were studied, on horizontal passing zones with similar traffic volumes (between 250 and 300 veh/hour).

TABLE 1 presents the field study and characteristics of each location.

ANALYSIS

Data reduction

Video data and trajectories cannot be analyzed easily. It is necessary to define different variables to describe passing maneuvers. These variables can be studied from a statistical point of view.

The total number of 234 observed passing maneuvers can be described by some basic variables, including times. Maneuvers with complete trajectory data can be described using a larger number of variables, including distances, speeds and accelerations, which can define all the stages of the pass.

TABLE 2 shows a list of variables considered in the study, and their values obtained in this field study.

Moreover, variables that describe the passing zone or the traffic characteristics, not only the individual passing maneuver, were also calculated, and have been already shown in TABLE 1.

Traffic effects

In the field study all the passing zones had similar traffic volumes. Relationships with hour traffic volumes are consequently not possible. Percent of heavy vehicles was between 15 and 23%.

However, the length of the passing zone is an important factor of the passing frequency in each zone. Long zones, like locations 1 and 2 had a high passing frequency, while short zones, under the recommendation of Spain criteria, had a very low frequency. Constant traffic volumes facilitate this comparison. These results agree with Harwood’s study of frequency of passes in short passing zones (3). In consequence, these short passing zones do not contribute much to the traffic efficiency of two-lane highways.

Travel on opposing lane

The main variables in the study were the time and distance travelled along the opposing lane. This time and distance measure the most important stage of the passing, because almost that all conflict situations at passing maneuvers are presented in this phase.

Time and distance, *t1* and *d1*, were analyzed. Multiple linear regression models were calculated in order to establish the main factors of both variables, and to explain their variability. Only significant variables were included in these models.

Time of travel on left lane in sample 1 (234 maneuvers)

The EQUATION 1 explains 42% of variability of *t1* caused by the number of passed vehicles, the type of passed vehicle and the length of the passing zone.

$$t1 = 1.454 + 0.003 \cdot ZONELENGTH + 3.233 \cdot NUMI + 1.602 \cdot TYPEI \text{ (R2=0.42)} \quad (1)$$

- "*TYPEI*" is the type of impeding vehicle (Codified as 0 for passenger cars and 1 for trucks).
- "*NUMI*" is the number of impeding (passed) vehicles.
- "*ZONELENGTH*" is the passing zone length in m.

Time of travel on left lane in sample 2 (58 maneuvers)

The EQUATION 2 explains the 52% of the variability of *t1* (only for simple passing, when there is only one impeding vehicle) caused by type of impeding vehicle and passing zone length.

$$t1 = 4.161 + 2.248 \cdot TYPEI + 0.003 \cdot ZONELENGTH \text{ (R2=0.52)} \quad (2)$$

Differential between passing and impeding average speeds (*dV*, during left lane travel) can be introduced as significant variable in the model (EQUATION 3).

$$t1 = 6.972 + 2.174 \cdot TYPEI + 0.003 \cdot ZONELENGTH - 0.121 \cdot dV \text{ (R2=0.67)} \quad (3)$$

The EQUATION 3 explains the 67% of variability of *t1* by inclusion in the model the differential *dV*. However *dV* is a very random variable, that not depends on any another variable of the maneuver. Variable *dV* cannot be controlled and should be treated as constant value in PSD models.

Speeds of impeding or passing vehicles have no influence on variable *t1*, in contrast to AASHTO or Hassan et al. models. Harwood et al. (3) propose also a constant time of left lane occupation, by observing passing maneuvers from video data (observed average time was 9.9 s according to Harwood).

Distance travelled on left lane in sample 2 (58 maneuvers)

72% of dispersion of distance travelled on left lane is explained with this model, in EQUATION 4. Relationships between *d1* and speed are stronger if the reference speed is the one of the impeding vehicle, named as *Vi* (km/h).

$$d1 = -55.247 + 61.182 \cdot TYPEI + 0.084 \cdot ZONELENGTH + 2.354 \cdot Vi \text{ (R2=0.72)} \quad (4)$$

Models for *d1* and *t1* in the same sample are coherent, because time and space on the left lane are related by average speed of passing vehicle. This coherence was verified.

Samples 1 and 2 were also compared, in order to extend results of sample 2 (better explained) to sample 1 (larger sample).

Regression models presented in this paper have only the objective of defining the most important correlations between these variables. The applicability of these models is restricted by the sample size. Safety levels assumed in these models were 50% (average values). Future models should assume higher levels of safety to cover human factors and be suitable as design or marking criteria.

Sample, and consequently scope of models, is reduced to Spanish rural roads with operating speeds (*V85*) within 94 and 120 km/h, and passing zone lengths within 250 and 1300 m. Only one passed vehicle must be considered. Passing vehicle was always a passenger car.

Out of these restrictions quality of models must be checked, in order to apply them to the construction of PSD models in further research.

Evolution of the vehicles along the passing maneuver

Relationships found in the regression analysis are established within average values of different variables of the passing. The consideration of "instant" values is necessary to explain the evolution of the vehicles along maneuvers. This analysis is now available with the explained methodology.

Time on the opposing lane was additionally divided in four sub-phases, between the following points:

1. Start of left lane occupation (start of *t1*).
2. Rear part of impeding abreast to front of passing: "head to tail".
3. Front part of both vehicles is abreast.
4. Rear part of passing abreast to front of impeding "tail to head".
5. End of left lane occupation.

The distribution of time in the different stages along a typical passing maneuver is described as follows. Any significant difference was not found between types of passed vehicles:

- Phase 1: between points 1 and 2: 0.32·*t1*.
- Phase 2: between points 2 and 3: 0.24·*t1*.
- Phase 3: between points 3 and 4: 0.04·*t1*.
- Phase 4: between points 4 and 5: 0.40·*t1*.

Abreast position is located at 56% of the time on left lane, in contrast to AASHTO model, which proposes 2/3 of *t1*.

FIGURE 2 shows the speeds of each vehicle along the passing maneuver. Time *t1* is normalized in order to compare the evolution of speeds of every individual pass, by assuming that *t1* in all maneuvers was the average time *t1*. Each colored line represents one passing or impeding vehicle of the total of 58 maneuvers (red represents the impeding vehicle and green the passing vehicle). Black broken lines cover the central tendency of 70 % of vehicles (percentiles 15^{th}, 50^{th} and 85^{th} are plotted).

Passed vehicle keeps its speed constant or accelerates up to 15 km/h (70% of data). Assumptions of constant speed of this passed vehicle can be wrong; despite they are usual in all the existent PSD models. Speed profile of the impeding vehicle is similar to the typical operating speed profile of vehicles that come from to curve sections to tangents. This can explain the acceleration of the slow vehicle.

Passing vehicle accelerates along the entire passing maneuver. Acceleration rate is normally lower (in up to 50% of maneuvers) in last stage of passing maneuver. The change of acceleration rate is located at the change from stage 3 to stage 4, when passing vehicles completes the pass of impeding vehicle.

At beginning of *t1* speed difference mean between passing and impeding vehicle is 12.5 km/h. An initial acceleration during perception-reaction stage should be considered. Moreover, there are a large number of possibilities between accelerative and flying passes.

Speed relationships

Average speeds of passing and impeding vehicles were calculated and compared with the operating speeds and design speeds on each passing zone.

FIGURE 3 shows the relationship between speeds of passing and impeding vehicles and design speeds, in comparison with AASHTO and Hassan models.

The observed data show a linear relationship between speeds of passing and passed vehicle and design speed. Passing vehicle speeds are higher than AASHTO or Hassan proposed speeds, especially for lower designs speeds (80 to 100 km/h)

Speed difference does not depend on design speed neither on type of passed vehicle. The average value of 23 km/h was the same for passenger cars and trucks, and was higher than in all the existing revised PSD models.

Critical position

Critical position is defined as the point of the last possibility of aborting a pass. From this point, it is better to complete the pass than to abort it. Many models like Glennon or Hassan et al. locate it in the point where sight distances to complete or abort the maneuver are equal.

Aborted maneuvers are less common on highways. Any aborted maneuver was not analyzed into the 58 completely described passing maneuvers. Estimations about the location of critical point are not possible in this study.

Opposing vehicle

Only in a few maneuvers an opposing vehicle was approaching and had influence on the behavior of passing and impeding vehicles. Only 15 of these maneuvers were analyzed including data of distances and speeds.

In these cases a uniform movement along the entire maneuver is adequate to represent the movement of the opposing vehicle, like assumptions of all the proposed models. Speed of opposing vehicle should be the 85^{th} percentile of operating speed in the specified direction of traffic. Using design speed could be unsafe.

PSD MODELS REVISION

After data analysis, different PSD models can be compared with obtained data. Most cited models are AASHTO, Glennon and Hassan's models.

PSD cannot be compared directly because field data is restricted to the left lane travel of the passing maneuver. In contrast left lane travel times and distances will be compared in order to verify the assumptions of those models.

AASHTO PSD model

AASHTO PSD model defines the passing sight distance as the sum of four components:

- Distance d_1: initial perception-reaction and acceleration distance.
- Distance d_2: left lane travelled distance.
- Distance d_3: clearance distance.
- Distance d_4: two thirds of d_2.

Existence of distance d_1 seems to be obvious, because of the need of a perception-reaction time and the initial acceleration. An initial acceleration before beginning the left lane occupation was observed. However, the starting point of the stage described by d_1 was not measured, due to the dependence of this point on driver's behavior.

Acceleration rates proposed by AASHTO depend on design speed level. They are between 0.62 m/s^2 and 0.67 m/s^2. Observed acceleration rates (average values in the acceleration stage along the entire maneuver) present very high dispersion. Percentiles 15^{th} and 85^{th} were 0.5 m/s^2 and 1.6 m/s^2. Dependence on speeds of passing or passed vehicle was not registered.

Consequently, AASHTO acceleration rate could be exceeded by almost that 85% of vehicles.

Distance d_2 of AASHTO model is the same distance that variable *d1* in the present study. This distance was also calibrated from different field studies.

The AASHTO model assumes that speed is not uniform, but calculates the distance d_2 as a uniform movement at the average speed of the passing vehicle V_p.

Comparison with field data, observed in FIGURE 4, uses the speed of impeding vehicle as speed of reference, because this speed has a stronger relationship with travelled distances than the speed of the passing vehicle in the observed maneuver. Tendency of observed data is shown by using simple regression lineal models. In this case, only the type and speed of vehicles are included as input variables of these tendency lines.

Similar relationships are found with times of travel on the opposing lane. However, this model proposes a time of travel on the opposing lane which increases with the speed, between 9 and 12 seconds, similar to average time *t1* for passed heavy vehicles in field data.

AASHTO model fits the distances to the average distances predicted if the passed vehicle is one truck. AASHTO model is conservative to represent the average distance *d1* for passed passenger cars, although calibration of the model was made from data of passenger cars (19).

Distance d_3 is the gap between passing and opposing vehicle when the return to the own lane is completed. Data observed in 15 maneuvers with opposing vehicles with influence on passing maneuver were compared with distance d_3. AASHTO proposed clearing gap can be considered as a lower threshold of observed distances, since only one case surpasses the AASHTO values.

Distance d_4 in AASHTO model represents the distance travelled by the opposing vehicle during the left lane travel of the passing one. Results of this research recommends consider 44% of left time travel instead 2/3. Moreover, assumed opposing speed by AASHTO model is equal to speed of passing vehicle. This could be often unsafe because speed of opposing vehicle can be higher than average speed of passing vehicle. Expected speed of opposing vehicle could be the 85th percentile of the free flow operating speed at the beginning of the passing zone.

With respect to the speed of vehicles and their relationship with the design speed, as shown in FIGURE 3, AASHTO model proposes a constant speed differential of 16 km/h, lower than the observed of 23 km/h. Speed of passed vehicle matches with observed data, since it is always between percentiles 50th and 85th of the registered speeds. Speed of passing vehicles was higher in observed maneuvers. That explains the differences in distances of travel on opposing lane.

PSD model of Hassan et al.

Hassan et al. PSD model (6) is an analytical PSD model, which calculates the sight distance using the equations of the movement of the three vehicles of the maneuver.

PSD is, according to Hassan, the sight distance required to complete a pass from the critical position. Before that, the author have defined an initial stage, necessary to reach the critical point, but not included in PSD.

The passing vehicle accelerates with uniform rate during the initial stage before critical point, until it reaches this point. The location of the critical point is calculated by making sight distances to complete and to abort equal. Moreover, critical point cannot be never situated beyond the abreast position. This reasonable assumption is the main difference between Glennon and Hassan’s model, since they use similar equations to calculate PSD.

After critical point, passing vehicle return to its own lane at constant speed, equal to design speed of the road.

Time headways between all vehicles are always assumed to be equal to 1 s. Speed differential between passing final speed and impeding vehicle speed depends on the design speed that is assumed as passing vehicle speed. Speed differential decreases with design speed.

Hassan’s basic assumptions define a movement of the passing vehicle very close to the observed passing maneuver, with lower acceleration rates after the critical position, always located next to the abreast position.

However, speed relationships are significantly different from the observed in this field study. At high speeds, the speed of passing vehicle is close to design speed, but at low speeds, the passing vehicle travels at speeds higher than design speed.

In all cases, average speed difference between passing and passed vehicle in observed maneuvers was 23 km/h, very far from the proposed speed differential.

By considering as reference speed the speed of the impeding vehicle, a comparison of distance travelled on the opposing lane is possible, and is shown in FIGURE 5.

The main differences between observed data and Hassan's model are visible at high speeds of the impeding vehicle. Hassan considers a nonlinear relationship between distance and speed that could not be observed in field data. Consequently, distances at speeds over 70 km/h are too far from observed distances.

CONCLUSIONS AND FURTHER RESEARCH

A new methodology to study passing maneuvers based on video data recording has been presented. Main advances of this methodology are the improved quality of video images and the possibility of determine the complete trajectories of the three participating vehicles with enough accuracy.

These advances are caused by the use of a higher number of cameras, which allows uniform video quality along the entire passing zone, and the use of a specific software that calculates the evolution of the vehicles with a frequency of at least 5 points per second.

The new methodology uses an existent equipment developed by the Universidad Politécnica de Valencia, and was used in the field study presented in the paper. The methodology allowed the research team to obtain a database of maneuvers with efficiency and enough accuracy.

The analysis has shown that new variables could be introduced in this model. An example of these new variables is the passing zone length. This length had influence on distance travelled along the opposing lane, because of drivers that have more space to do the pass are used to extend their travelled distance on this left lane. The inclusion of this variable can adequate the marking criteria to long and short passing zones. The passing zone length can be only included in statistical models, due to the problems to describe it by analytical formulations of PSD.

An additional analysis of those observed maneuvers was possible in order to compare data with some existing PSD models.

PSD model of AASHTO, used as design criteria in US, is also based on field data. Maneuver explanation and proposed values can generally be accepted. AASHTO proposes distances always over percentiles 50^{th} of observed distances.

However, speeds of the participating vehicles could be redefined. Speed differential of 16 km/h is lower than the observed in the passing maneuvers of this study (23 km/h). This was also observed in all other existing PSD models.

PSD model of Hassan et al. presents a complete description of the evolution of the passing vehicle. An initial acceleration phase was always registered and after that, acceleration rates are lower.

However, speed relationship of Hassan's PSD model is not close to observed speeds. Differences of 10 km/h with observed data were found in impeding vehicle speeds. Several assumptions of this PSD model could be checked with field data.

Applicability of obtained results is restricted to Spanish rural roads, due to the origin of the observed data. Regional variations are possible, and it suggests applying the proposed methodology in other sites.

Further applications of the developed methodology are possible. More observations in locations having nearly minimum recommended passing zone lengths would be beneficial, to understand better the effect of that length.

Extend the video recording to other passing zones will allow to consider more additional variables, that could have an important influence on PSD. For example, it would be possible to study the effect of night lighting conditions in passing zones, in comparison with day light time, or to analyze the influence of the grade of the highways on passing maneuver. Night visibility is also possible using the cameras of the Mobile Traffic Laboratory, with a small reduction in accuracy, thanks to the infrared filters of cameras.

Study of passing maneuvers involving a truck as passing vehicle is necessary too.

Variables related to the opposing vehicle should be more times observed in order to validate existing criteria or propose new models. Moreover, an extension in sample size of the field study can make the construction of a new PSD model possible.

Driving behavior related characteristics cannot be easily studied with this methodology, because it allows video recording from an external point of view.

The construction of a PSD model should eventually consider traffic operation and safety related aspects, which can help proposing the most adequate formulation.

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LIST OF TABLES AND FIGURES

Passing Zone	1	2	3	4
Location	Casinos CV-35	Vilamarxant CV-50	Carlet CV-50	Carlet CV-50
Date	Feb, 16th 2010	Mar, 11th 2010	Apr, 4th 2010	Apr, 4th 2010
Duration (hours)	4	4	3	3
Time at start	9:00	8:30	9:00	9:00
Weather – Lighting	Cloudy	Sunny	Sunny	Sunny
Road Surface	Dry	Dry	Dry	Dry
Geometric characteristics				
*Length of the passing zone (m)	1,100 – 1,300	600 - 850	245-280	270-260
Grade	0%	0%	0%	0%
Traffic conditions				
Average hour traffic volume (veh/h)	268	282	285	285
% of heavy vehicles	23	17	15	15
*Operating speed (km/h)	119-111	95-93	92-100	92-100
*Free flow operating speed (km/h)	125-120	98-94	97-103	97-103
**Design speed (km/h)	120	80	90	90
**Speed limit (km/h)	100	100	100	100
Observed maneuvers				
Number of observed passing maneuvers	118	100	8	8
Passing trajectories obtained	14	35	4	5
Passing rate (Pass/veh) %	11.0	8.9	0.9	0.9
Passing frequency (Pass/hour)	29.5	25.0	2.7	2.7

**The two numbers indicate the values corresponding to the two directions of the road*

***Design speed is defined (according to Spain design criteria (13)) as a reference speed for highway sections of at least 2 km. Posted speed limit can be higher in shorter sections.*

TABLE 1 Field study locations and characteristics

	Code	Unit	15^{th} Perc	Mean	85^{th} Perc	Mean Car	Mean Truck
Sample 1 and 2: basic variables							
Number of passed vehicles	*NUMI*	-	-	-	-	-	-
Type of passed vehicle	*TYPEI*	-	-	-	-	-	-
Time travelled on left lane (only simple passes)	*t1*	s	5.4	7.6	10.2	6.36	8.95
Time between return to the own lane and crossing with opposing vehicle, if exists	*t2*	s	2.4	3.4	5.0	not significant dif.	
Sample 2: trajectory data reduction (Only simple passes)							
Length of passing vehicle	*Lp*	m	4.0	4.5	5.0	-	-
Length of passed vehicle	*Li*	m	4.5	7.8	11.5	4.5	11,3
Distance travelled on left lane by passing vehicle	*d1*	m	130	193	267	170	222
Distance travelled by passed vehicle	*d1i*	m	88	147	204	130	170
Average speed of passed vehicle	*Vi*	km/h	53	69	74	not significant dif.	
Average speed of passing vehicle	*Vp*	km/h	75	92	107	not significant dif.	
Average speed difference	*dV*	km/h	15	23	33	not significant dif.	
Gap between passing and passed vehicles at begin of maneuver	*h1*	m	5	13	16	not significant dif.	
Gap between passing and passed at end of maneuver	*h2*	m	9	12	21	not significant dif.	
Gap between passing and opposing vehicle at end of maneuver (clearance distance)	*dp-o*	m	98	163	243	not significant dif.	
Average acceleration of passed vehicle before the abreast position	*a*	m/s^2	0.5	1.0	1.6	not significant dif.	

TABLE 2 Variables of passing maneuver

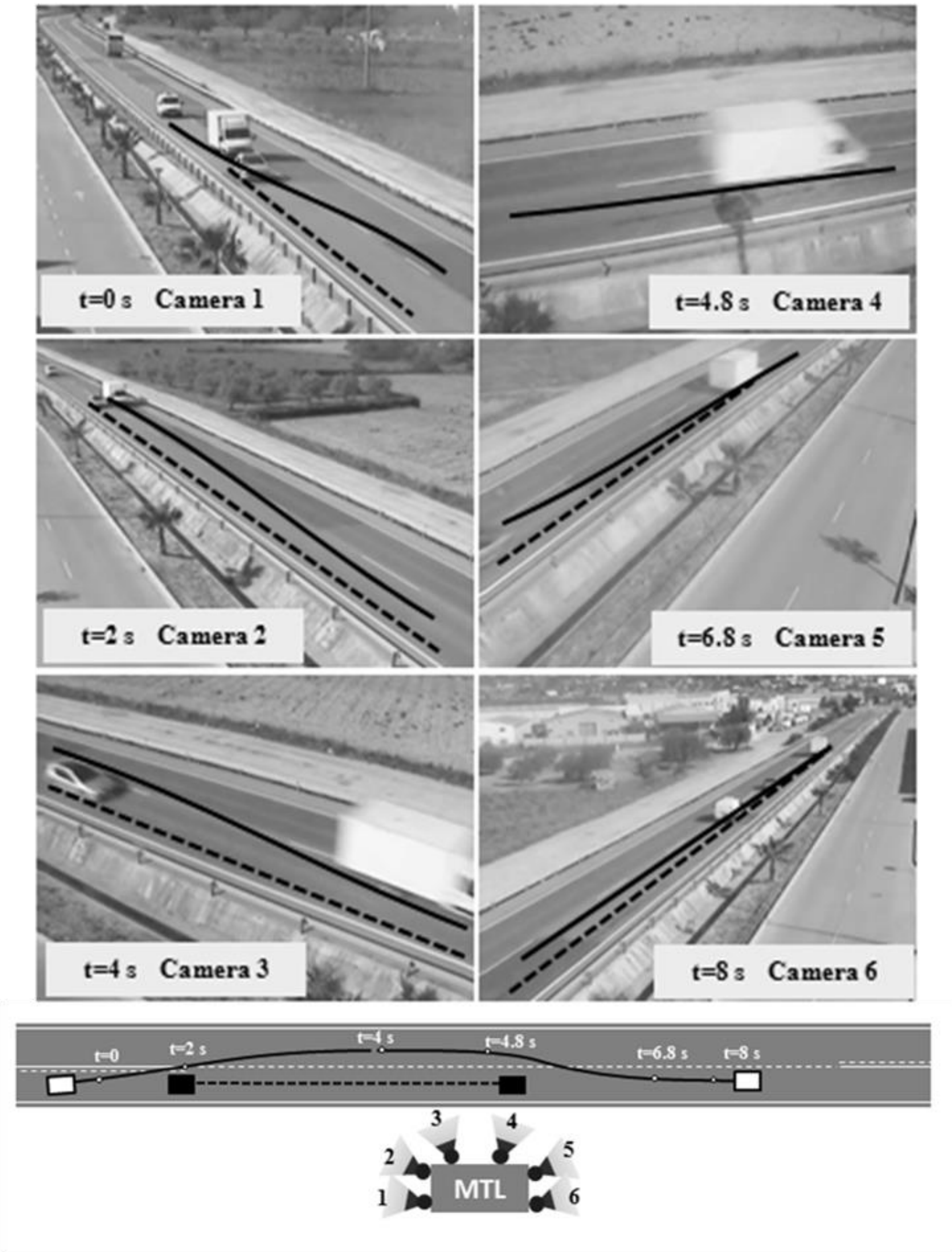

FIGURE 1 Sample frames of a passing maneuver observed at 6 cameras and location of the Moving Traffic Laboratory (MTL) near the studied passing zone

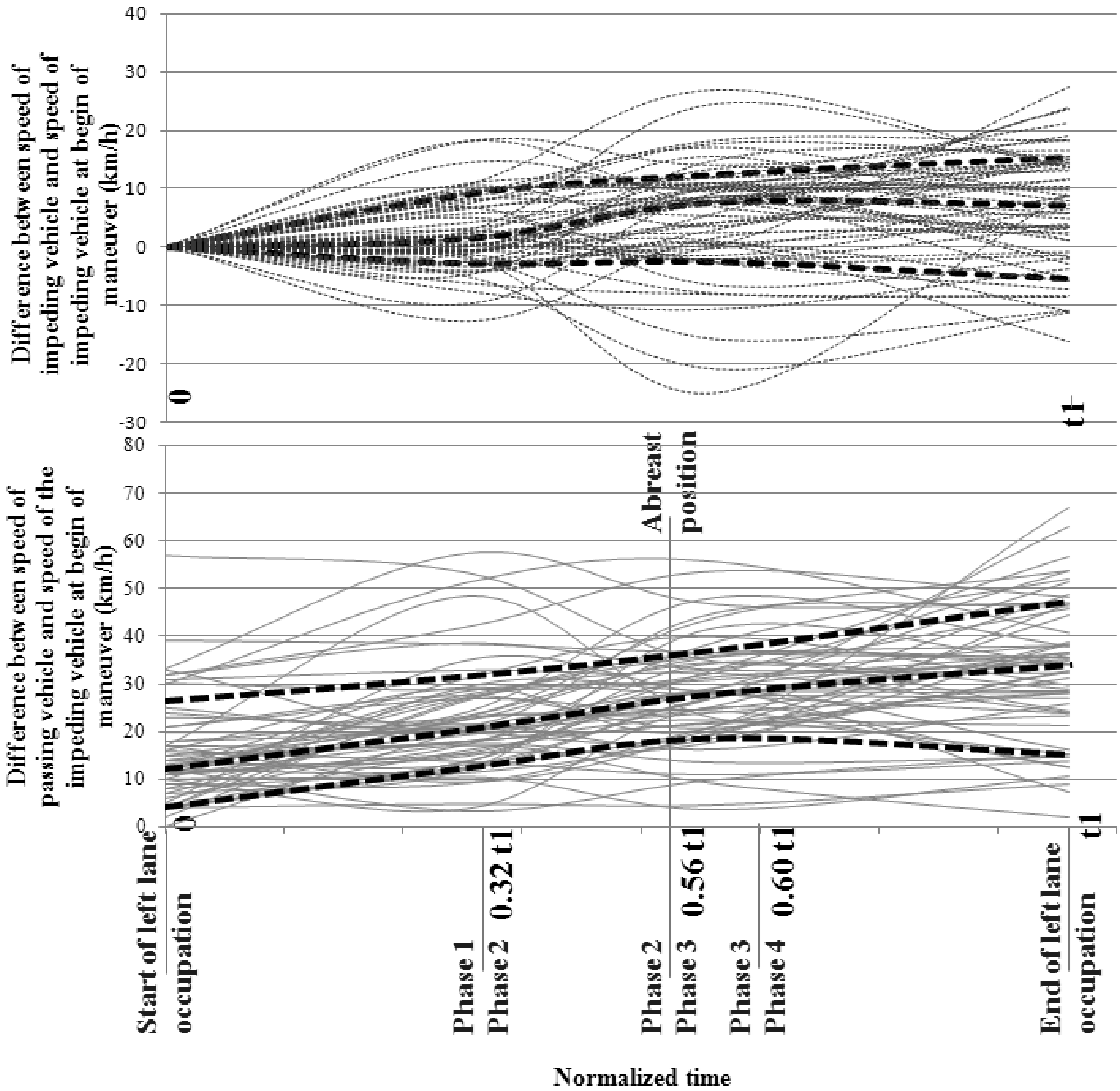

FIGURE 2 Speed variation in passing maneuvers. Plotted lines represent relative speed respect of the initial speed of the impeding vehicle. Broken lines are percentiles 15, 50 and 85th.

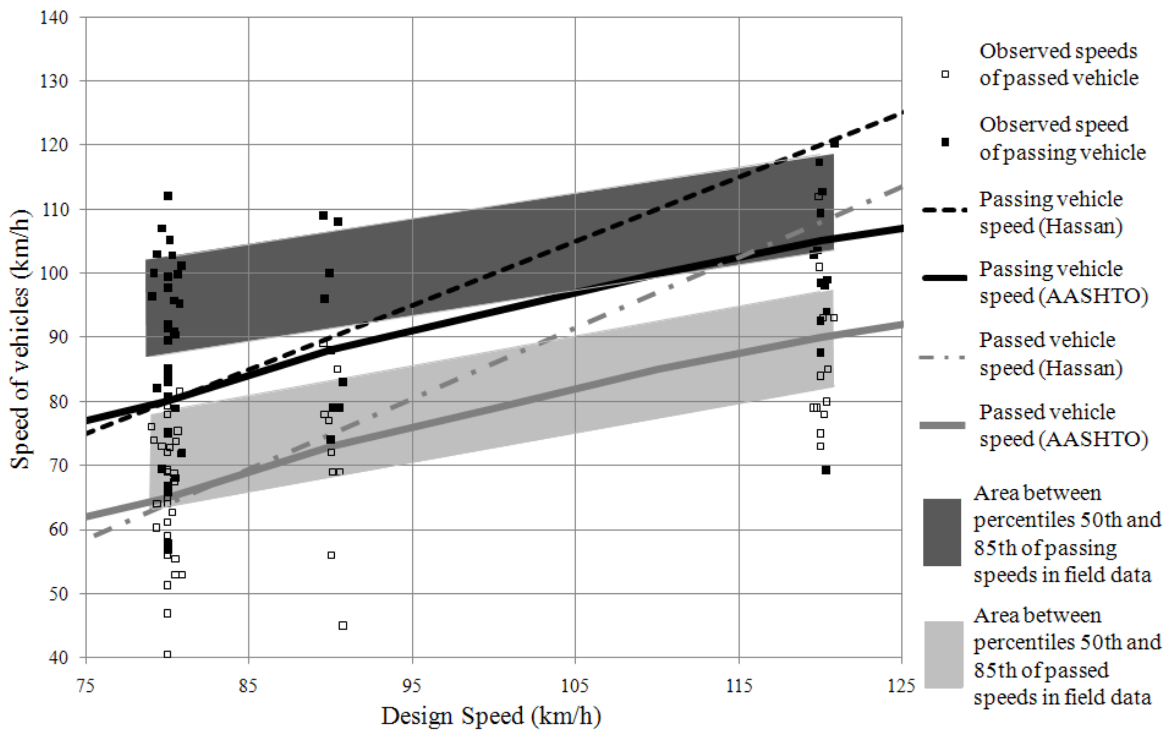

FIGURE 3 Speeds of passing and impeding vehicle vs. design speed

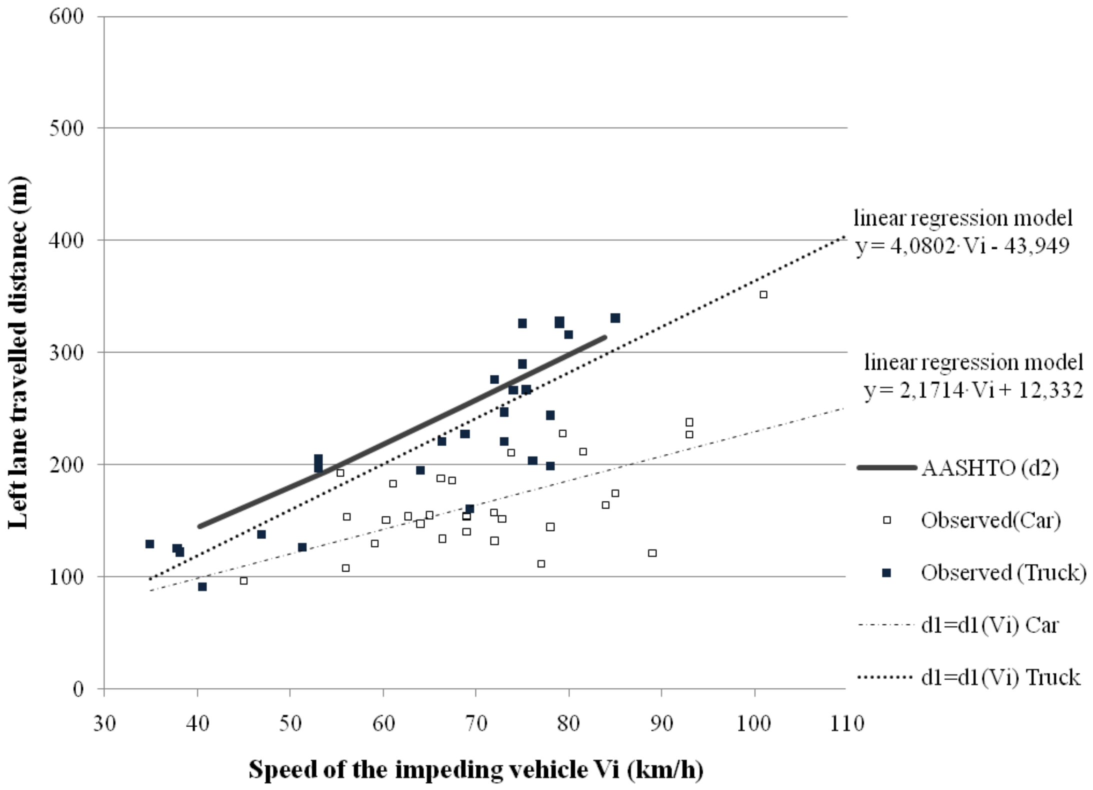

FIGURE 4 Comparison of left lane distance in AASHTO model

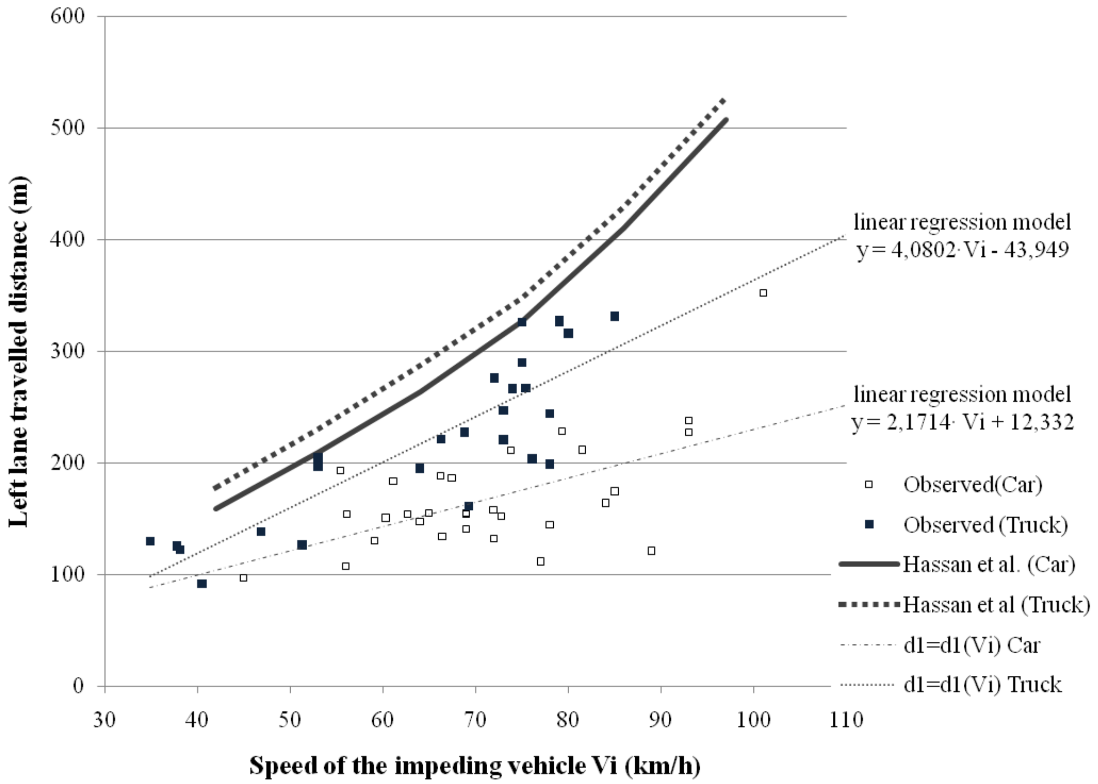

FIGURE 5 Comparison of left lane distance in Hassan et al.