Characterization of Passing Zones based on Curvature Change Rate: Operational Impact

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ABSTRACT

Geometric design intends to provide operation efficiency, comfort, safety and convenience for the motorists. The level-of-service criteria for two-lane highways is based on percent time spend following (PTSF) and average travel speed (ATS), and both are affected by the lack of passing opportunities. Passing zones are provided where sight distance is greater than the minimum passing sight distance; and their length and frequency depend mainly on the physical constrains and cost factors.

The objective of the research is to analyze the relationship between the highway horizontal alignment, characterized by curvature change rate (CCR), and its expected level-of-service (LOS).

For the research, 25 Spanish two-lane rural highways were selected. Geometry was obtained from Google Earth using a highway recreation software. CCR was calculated and used to identify uniform segments. The sample included 56 uniform segments (112 directional segments) and 451 passing zones. The statistical analysis showed that CCR decreased percentage of passing zones and average passing zone length. After the geometry-based characterization of passing zones, 8 of the segments were introduced and simulated in the TWOPAS simulation model, which was previously calibrated and validated with passing data from Spanish highways. The analysis of the simulation results provided models of ATS depending on CCR and percentage of passing zone and PTSF depending on percentage of passing zone. The estimated level of service differed 21% to the studied scenarios, mainly because of the HCM overestimation of PTSF. In 70% of the scenarios with high traffic volume and sinuosity, HCM overestimated the level-of-service.

The results of this research will help highway designers and practitioners to predict operational performance based on CCR and expected hourly traffic volume, and could be used as design and management criteria.
INTRODUCTION

Geometric design intends to provide operation efficiency, comfort, safety and convenience for the motorists (1). In two-lane highways, faster vehicles that want to move ahead of slower vehicles need to pass them using the oncoming lane. Passing zones can be provided along the segment where the sight distance ahead is equal to or greater than the minimum passing sight distance, so as warrants for safety. In addition, the MUTCD (2) defines a minimum value for the distance between no-passing zones. Designs with infrequent passing sections may not provide enough passing opportunities for efficient traffic operations.

The Highway Capacity Manual (HCM) (3) is used to analyze the level-of-service (LOS) of two-lane highways. The procedure is based on three measures of effectiveness, depending on the type of highway. On Class I highways, LOS is defined in terms of both average travel speed (ATS) and percent time spent following (PTSF), as mobility and freedom to maneuver are important to motorists. On Class II highways, PTSF is used to define LOS, while on Class III LOS is defined in terms of percent of free-flow speed (PFFS). The three measures depend on some geometric and demand data, such as percent of no-passing zone, base design speed or traffic volume. The HCM procedure should be applied to uniform directional segments of two-lane highway. Segment boundaries should be established at points where a change occurs in terrain, cross section, facility classification, or demand flow rate. Significant variations on horizontal alignment are not included, neither on the evaluation procedure nor the uniform segment identification. For the same design speed, alternative horizontal alignments can be designed with more or less sinuosity.

There is a large amount of published literature that presents operating speed as a function of road parameters; focusing mainly on the influence of horizontal curvature on free-flow speeds (4). Given the relationship between operating speed and design elements, the average travel speed of a segment would likely be affected by a higher presence of curves. The German methodology to determine uniform segments depends also on the highway sinuosity (5). The curvature change rate (CCR) is defined as the sum of deflection angles divided by the length of the segment. The boundaries for uniform segments are set in significant variations of CCR. This methodology reflects better inertial operating speed variations (6) and was considered for safety evaluations in Italy (7). Highway sinuosity may also affect platooning. Sinuous horizontal alignments may have more passing sight distance restrictions than straighter alignments; so reducing the percentage of passing zones and passing opportunities.

Microsimulation is a useful tool to analyze traffic operation. The Interactive Highway Safety Design Model (IHSDM) includes a passing model as part of the Traffic Analysis Module (TAM, previously named TWOPAS). This model was used to determine the adjustment factors of the HCM (8); however, authors assumed TWOPAS initial calibration based on 1970’s data and no indications on the precision of the adjustment were given (9). Harwood et al. also used TWOPAS to determine the operational contribution of short passing zones (10), also assuming the initial calibration. Recent studies calibrated TWOPAS with field data to analyze ATS and PTSF in Brazil (11) and Spain (12), or the addition of climbing lanes to facilitate passing (13). Besides TWOPAS, CORSIM (14), TWOSIM (15, 16), RutSim (17), Ghods (18) and Aimsun (19) have incorporated passing maneuvers to the two-lane highway module. Nevertheless, TWOPAS is the only software that relates traffic performance to geometry, as horizontal curves may reduce speeds desired by drivers in curve and its approach (20). Consequently, it could automatically achieve more realistic speed profiles, based on the horizontal alignment.

Research motivation

Expected traffic operation is another possible criterion for passing sight distance design on two-lane highways. Current evaluation of traffic performance excludes horizontal alignment variations, which could produce more or less sinuous alignments and thus affect potentially to both average travel speed and percentage time spent following. The objective of this research is
to analyze the relationship between the highway horizontal alignment, characterized by curvature change rate and its expected level-of-service.

OBJECTIVES AND HYPOTHESES

The objective of the research is to analyze the relationship between the highway horizontal alignment, characterized by curvature change rate (CCR), and its expected level-of-service (LOS).

The study included the following tasks:

- Recreate the horizontal alignment and passing zones of 25 two-lane highways and determine uniform segments based on CCR.
- Evaluate the correlation on uniform segments between CCR and passing zones.
- Analyze the traffic performance of uniform segments with different CCR and passing zones by using traffic microsimulation.
- Estimate the level of service considering horizontal alignment.
- Compare the results with the HCM procedure.

The following hypotheses have been established:

- Average passing zone length and percent of passing zone can be described by the curvature change rate.
- Curvature change rate can predict average travel speed. The higher CCR, the lower ATS.
- Curvature change rate can predict percent time spent following. The higher CCR, the higher PTSF.
- Current Highway Capacity Manual procedure will not accurately estimate average travel speed and percent time spent following in sinuous segments.

GEOMETRIC CHARACTERIZATION OF PASSING ZONES

In the first part of the study, a sample of two-lane highway segments and their passing zones were geometrically characterized based on the curvature change rate.

Methodology

A sample of 25 two-lane highways in Spain was selected. Highways were located in rural environments, without additional passing or climbing lanes, and randomly distributed throughout Spain. Selection criteria included: sinuosity (CCR), terrain (level or rolling), annual average daily traffic (AADT), and posted speed limit.

Horizontal alignment of each highway was obtained from Google Earth aerial photography using specific software developed by Camacho-Torregrosa et al. (21). The software recreates the horizontal alignment of existing roads using the heading direction instead of curvature. Each geometric element (tangent, curve or clothoid) is mathematically defined by the heading direction and includes stitching relationships between consecutive geometric elements; so the analytical solution is unique and sufficiently accurate for the research. Entry data consisted on selecting from images a sequence of (x,y) data points that follow the centerline of the road.

The next step was the calculation of curvature change rate (CCR) of every single element, according to the Equation 1.

\[
CCR_{element} = \frac{deflection\ angle_{element}}{length_{element}}
\]  

Then, the cumulative deflection angle and cumulative distance along the road were plotted (Figure 1). Tangents presented no CCR while curves increased the cumulative CCR.
Boundaries were the points where CCR changed significantly; then uniform road segments were then identified as segments with similar cumulative CCR slope or gradient. The analysis of the 25 two-lane highways lead to 56 uniform segments.

Figure 1. Example of CCR plot to identify uniform segments

For each uniform segment, the average CCRij was calculated as the slope of the linear regression between the cumulative distance and the cumulative angle. Figure 1 shows one example of two uniform segments identification and their CCR calculation. Passing zones were then characterized using Google Earth aerial photography and Google Street View images. Travel directions were considered separately, as their passing zone length or available sight distance varied. A total of 451 passing zones were identified. For each passing zone (k) of each road segment (j) in the road (i) were collected:

- Initial and end stations.
- Passing zone length (m).
- Available sight distance at start and end of the passing zone (m).

The isolated passing zones’ characteristics were aggregated along the uniform segments. As passing zones varied depending on travel direction, the number of directional uniform segments was 112. In 103 of those segments there was, at least, one passing zone. Average passing zone length and percent of passing zone were calculated for each directional uniform segment.

Results

Passing zones characteristics were correlated to the horizontal alignment, using the average passing zone length (PZL), percentage of passing zones (PPZ) and curvature change rate (CCR). Linear regression models were developed in R, with the results summarized in Table 1.

Table 1 shows the results of the estimation of PZL and PPZ models. As can be seen, both models were statistically significant at the 95% confidence level, as verify the F-statistic. Residuals were normally distributed, fulfilling the assumptions of linear regression. The effect of CCR was significant in both cases: the higher CCR of the segment, the shorter average passing zone length and percentage of passing zone.
## Table 1. Estimation models for passing zone length (PZL) and percentage of passing zone (PPZ)

<table>
<thead>
<tr>
<th>Coefficients:</th>
<th>Coefficients:</th>
</tr>
</thead>
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<tr>
<td>( \text{log(PZL)} )</td>
<td>( \text{PPZ} )</td>
</tr>
<tr>
<td>Estimate</td>
<td>Std. Error</td>
</tr>
<tr>
<td>(Intercept)</td>
<td>6.6028311</td>
</tr>
<tr>
<td>( C C R_{ij} )</td>
<td>-0.0038070</td>
</tr>
</tbody>
</table>

| Residual standard error: 0.4588 on 101 degrees of freedom | Residual standard error: 0.1968 on 110 degrees of freedom |
| Adjusted R-squared: 0.4139 | Adjusted R-squared: 0.3358 |
| F-statistic: 71.32 on 1 and 101 DF | F-statistic: 55.61 on 1 and 110 DF |
| p-value: 2.33e-13 | p-value: 2.17e-11 |

The models had an adjusted R-squared of 0.41 and 0.34, respectively. The correlation was significant despite the fact that only horizontal alignment was considered. Vertical alignment can also restrict available sight distance and reduce the length or number of passing zones. Other factors, such as intersections or bridges, can also limit the passing zones.

## MICROSIMULATION STUDY IN TWOPAS

### Field study
Field data characterizing traffic operations was collected on four passing zones in one rural highway in Valencia (Spain). Design speed, as well as posted speed limit, is 100 km/h; while annual average daily traffic (AADT) was 5,577 veh/day in 2010. Observed two-way traffic volumes ranged from 120 to 1,000 veh/h and traffic flows were mainly balanced. Passing zone lengths were between 265 and 1,270 m.

Data was collected using two coordinated high definition (HD) video cameras located at the beginning and ending of the passing zones. They were located at the roadside and were not perceived by drivers. From this data, time headways, percent followers, average travel speed and number of passes were calculated. A total of 1,649 passes were observed during the 53 hours of video (9.5 hours per location). This data has been previously used to analyze operational performance of passing zones (22), calibrate traffic performance measures (23), or safety analyses of passing zones (24).

### Calibration and validation
TWOPAS microscopic simulation model was calibrated to reproduce the traffic conditions observed in the field. Genetic algorithms (GA) was used to search for a set of model parameter values that minimized the differences between the observed and simulated traffic streams.

Firstly, horizontal and vertical alignment were recreated from GPS data (10 Hz). Cross section, available sight distance profile, passing zones and speed limits were also introduced in TWOPAS. Traffic composition, as well as drivers’ desired speed (average and standard deviation) per vehicle type, were obtained from the videos. Moreover, vehicle’s performance (maximum acceleration, overall length, weight/net horsepower ratio, etc.) was adapted to the observations. The calibration used 30 traffic periods of 15 minutes.

Secondly, the genetic algorithm by Bessa and Setti (11) was adapted to our field data, which included the number of passing maneuvers. GA is based on a natural selection process that mimics biological evolution. The algorithm repeatedly modifies a population of individual solutions. At each generation, the algorithm selects the fittest individuals and uses them as parents to produce the children for the next generation. Individual’s genome is recombined with the best individual of the population (crossover with elitism). Over successive generations, the
population would evolve towards an optimal solution. In order to search for the global solution rather to converge to a local solution, mutation (random modification the child genome) and predation (substitution of the less fit individuals for new random individuals) can be introduced at some generations.

Thirdly, parameters of the calibration and GA were selected, as well as defined the fitness function. TWOPAS calibration parameters should be adjusted by users and represent local driver behavior. The selected parameters were: car-following sensitivity factor (ZKCOR), stochastic driver type factor for each driver type (BKPM1-BKPM10) and probability of passing reconsideration (PREC). The fitness function evaluated the difference between the simulation and field data on 20 variables: number of passes (2), percent followers at the end of the segment (2), average and standard deviation of passenger car and truck speeds (8) and 15th and 85th percentile of speed distribution (8). Three combinations of weightings were tested in 4 generations of 40 individuals and 5 random seeds; for the 30 traffic streams. The best weighting combination was selected. Then, GA crossover, mutation and predation parameters were also tested in three combinations, using 20 generations of 40 individuals. More than 360,000 simulations were used during this initial calibration.

Finally, the GA was executed with best combination of GA parameters and fitness function weightings. The GA used 480,000 individual simulations to find the optimal solution (30 traffic streams, 80 generations, 40 individuals, 5 random seeds). The error was reduced to half, compared to the initial population.

After the calibration, the model was validated with additional 60 traffic streams. The error was similar to the final error of calibration.

Case study scenarios
After completing the calibration and validation, the case study scenarios were generated. A sample of 8 uniform CCR segments, with 100 km/h posted speed limit, were selected. The segments were selected from the previous analysis. Horizontal alignment, posted speed limit, passing zones and available sight distances were recreated in TWOPAS. Level terrain and constant 0.5 % grade were used.

Table 2. Case study scenarios characteristics

<table>
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<tr>
<th>Segment</th>
<th>Scenario</th>
<th>CCR (gon/km)</th>
<th>PZL (m)</th>
<th>estimated PZL(CCR) (m)</th>
<th>PPZ (%)</th>
<th>estimated PPZ(CCR) (%)*</th>
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*Estimated using Table 1 equations
As both directions had different average passing zone length, the sample was 16 uniform directional segments. They covered different CCR (from 7.2 to 177.5 gon/km), percentage of passing zone (from 32% to 68%), and average passing zone length (from 335 to 1049 m). Not all the scenarios had similar PPZ and PZL to the PPZ and PZL estimations based on CCR. Table 2 summarizes their characteristics.

The uniform CCR segments were evaluated for 100 to 1,500 veh/h, with steps of 100 veh/h. Consequently, 16 traffic scenarios were generated covering the entire range of directional traffic volumes. In all cases, the directional split of traffic was 50/50 and two percentage of trucks was considered: 0 and 10%. A free-flow speed of 100 km/h was specified, according to the calibration. For each CCR segment and traffic volume, 15 replicate runs were made. The replicates varied the random seed and calibration parameters. Both of them were randomly selected from one list of 25 random seeds and 50 calibration parameters combinations.

The TWOPAS model provided a total of 7,200 directional scenarios.

### Analysis and results

Average travel speed (ATS) and percent time spent following (PTSF) were obtained from the directional scenarios. Traffic performance was correlated to the average passing zone length (PZL), percentage of passing zones (PPZ) and curvature change rate (CCR). Linear regression models were developed in R. The best models for ATS and PTSF are summarized in Table 3.

#### Table 3. Estimation models for average travel speed (ATS) and percent time spent following (PTSF)

| Coefficients: | Estimate | Std. Error | t value | Pr(>|t|) | Coefficients: | Estimate | Std. Error | t value | Pr(>|t|) |
|---------------|----------|------------|---------|---------|---------------|----------|------------|---------|---------|
| (Intercept)   | 8.020e+01 | 3.114e-01 | 257.52  | <2e-16  | (Intercept)   | -92.214510 | 0.327653   | -281.4  | <2e-16  |
| Vd            | -1.465e-02 | 8.198e-05 | -178.75 | <2e-16  | log(Vd)       | 26.536602  | 0.044208   | 600.3   | <2e-16  |
| CCR           | 6.681e-02  | 2.767e-03  | 24.14   | <2e-16  | PPZ           | -0.101324  | 0.003322   | -30.5   | <2e-16  |
| PPZ           | 1.714e-01  | 6.678e-03  | 25.66   | <2e-16  |               |          |            |         |         |
| CCR:PPZ       | -3.426e-03 | 6.233e-05  | -54.97  | <2e-16  |               |          |            |         |         |

Residual standard error: 2.735 on 7075 degrees of freedom
Multiple R-squared: 0.8882, Adjusted R-squared: 0.8882
F-statistic: 1.406e+04 on 4 and 7075 DF, p-value: < 2.2e-16

Both models were statistically significant at the 95% confidence level and their variables were also significant. Normality of the residuals was verified, fulfilling the assumptions of linear regression. The correlation was strong in both cases, with an adjusted R-squared of 0.88 and 0.98, respectively. As seen, average travel speed depended on directional traffic volume, CCR and percentage of passing zones, while PTSF only depended on directional traffic volume and percentage of passing zones.

Figure 2 represents the model estimates for average travel speed. For the same percentage of passing zone, ATS decreases as the CCR increases: the more sinuous the highway, the slower average speed. The differences caused by CCR are higher as the percentage of passing zone increases. For instance, the effect of increasing the CCR 50 gon/km results in reducing 1.8 km/h the average travel speed with PPZ equal to 30%, and this reduction is 8.6 km/h with PPZ = 70%. On the other hand, for the same CCR, ATS increases as PPZ increases.

Figure 3 shows the estimated percent time spent following depending on the directional traffic volume and percentage of passing zone. As seen, the effect of directional traffic volume was greater than PPZ. Given the traffic volume, the maximum difference on PTSF caused by PPZ was 4%.
Figure 2. Model estimation for average travel speed depending on directional traffic volume, CCR and percentage of passing zones (grey boxes)

Figure 3. Model estimation of percent time spent following

DISCUSSION

Traffic performance
The differences between the Highway Capacity Manual (3) and the developed models are discussed in this section. To do so, the HCM procedure was applied to the simulated scenarios.
One macro in Excel was developed to calculate the equivalent passenger cars and adjustment factors, and the percentage of passing zones was converted to percentage of no-passing zones. The differences in ATS and PTSF for the simulated scenarios are represented in Figure 4 and Figure 5. Positive values indicate that HCM overestimated the value, while negative values indicate that HCM underestimate the value.

Figure 4. Difference in average travel speed between the HCM estimation and the model prediction depending on directional traffic volume, CCR and percentage of passing zones (gray boxes)

Percentage of passing zones was divided in four groups with similar sample. CCR was classified in three categories: low (CCR <50 gon/km), medium (50<CCR<75 gon/km) and high (CCR> 75 gon/km). The maximum CCR was 177 gon/km (Table 2). As seen in Figure 4, not all the PPZ groups had the same CCR categories, however the trends could be extrapolated.

Surprisingly, ATS is underestimated in low CCR highways, since straighter scenarios were used to develop the HCM procedure. The differences increase with traffic volume and are very similar in the scenarios with PPZ between 30 and 50 %. On the other hand, medium CCR highways present average better results. Finally, the HCM overestimates ATS in highways with high CCR. The maximum differences are in low traffic volume, which could increase to 20 km/h. Consequently, HCM procedure may not be applicable to highways with high CCR (CCR>75 gon/km) and posted speed of 100 km/h. It should be noted that the maximum CCR for a 100 km/h design speed highway would be 141 gon/km according to the Spanish design guideline (25); while the maximum CCR for a 100 km/h posted speed limit highway would be 195 gon/km (26). Figure 5 presents the difference in PTSF between the HCM estimates and model predictions. The differences are higher in low traffic volumes, for all percentage of passing zone. As the percentage of passing zone increased, the differences are lower because the scenario would be more similar to the scenarios used to develop the HCM. The HCM overestimated PTSF in 12% for very low traffic flows, and around 5% in directional traffic volumes of 300 veh/h. The differences are stabilized from directional traffic volumes of 600 veh/h and were lower than 2 %. Therefore, the HCM procedure should be updated to current driver behavior that leads to lower PTSF.
Figure 5. Difference in percent time spent following between the HCM estimation and the model prediction depending on directional traffic volume and percentage of passing zone.

Level of service

The levels of service (LOS) were calculated applying the Highway Capacity Manual (3) criteria for Class I and II two-lane highways to the model predictions and the HCM estimations. Then, LOS for each scenario was compared. Both classes were considered as roadway geometry does not affect this classification. Figure 6 shows the percentage of scenarios where the HCM estimation and model prediction differ.

Figure 6. Percentage of scenarios with different estimated level of service.
The percent of scenarios with similar LOS estimation were lower for Class I highways (79.2 %) than Class II highways (86.9 %). In fact, the differences were higher for all the traffic volumes. In Class I highways, sinuous highways with high traffic volume were prone to estimate different values (70 %), as the estimation of ATS was less accurate. This value was reduced for medium and low CCR highways, for the same traffic volume range (8 and 5%, respectively). In lower traffic volumes, the differences were less dependent on CCR, although they were high (between 36 and 48 %).

For class II highways, the differences were lower and the influence of CCR was not significant.

CONCLUSIONS AND FURTHER RESEARCH

The operational efficiency of many two-lane highways depends on the opportunity for faster drivers to pass slower drivers. Designs with infrequent passing zones may not provide enough passing opportunities for efficient traffic operations. The Highway Capacity Manual presents the procedure to evaluate traffic performance in two-lane highways. However, this procedure does not consider variations on horizontal alignment that could affect both average travel speed and percent time spent following.

The objective of this research was to explore the potential impact of horizontal alignment in the expected traffic performance. The selected aggregate measure for horizontal alignment was the curvature change rate (CCR), which is used to define uniform roadway segments. On the first part of the study, the correlation between CCR and passing zones characteristics was evaluated. On the second part of the study, the traffic performance of uniform CCR segments was estimated using traffic microsimulation.

The main conclusions of this study are:

- Relationships between curvature change rate, average passing zone length and percentage of passing zones could be used to design and predict passing opportunities on one road segment. A relationship between curvature change rate and average passing zone length was defined with coefficient of determination equal to 41 %. The relationship between curvature change rate and percent of passing zones had a coefficient of determination of 34 %.

- Curvature change rate, percent of passing zone, directional traffic volume and average travel speed present a strong correlation ($R^2_{adj} = 88 \%$). The geometric variable with higher influence was curvature change rate, and the differences were higher as the percentage of passing zone increases. Average passing zone length have a minimal impact on average travel speed.

- The strongest relationship found in this study was between directional traffic volume, percentage of passing zones and percent time spent following ($R^2_{adj} = 98 \%$). No other variables were statistically significant at a 5 percent alpha level. The impact of percentage of passing zones is weaker than directional traffic volume and can cause a maximum variation of 4 %, given the traffic volume.

- Highway Capacity Manual overestimates average travel speed in low traffic volume and sinuous highways, which could be around 20 km/h. HCM procedure may not be accurate enough to estimate average travel speed in sinuous highways (CCR>75 gon/km).

- The determination of uniform road segments into different geometric types is necessary for evaluating traffic performance. To better establish the boundaries, the German methodology based on curvature change rate is proposed. This criterion should be added to the current criteria: terrain type, cross section, facility classification and demand flow rate.

- Highway Capacity Manual overestimates percent time spent following in low traffic volume (up to 12 % difference), for all percentage of passing zone, although they
decrease as the percentage of passing zone increased. The differences are stabilized from directional traffic volumes of 600 veh/h.

- Most of the scenarios estimate the same level-of-service than the Highway Capacity Manual (80 %). The level-of-service overestimation is high in scenarios with high traffic volume and sinuosity (70 % of the cases); and the level-of-service is underestimated in low traffic volume, for all CCR (38 - 50 % of the cases).

The developed traffic models could be used in design to estimate traffic performance and determine the level of service that will be provided for the proposed design alternatives. The level of service provided by the proposed design should be compared to the highway agency’s desired level of service for the project. Nevertheless, the authors acknowledge that further research is needed to evaluate the impact of terrain type, posted speed or directional split. Moreover, vertical alignment would be included on the future to improve the geometric characterization models of passing zones.

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