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TIME-BASED CALIBRATION OF THE INERTIAL OPERATING SPEED TO ENHANCE THE ASSESSMENT OF THE GEOMETRIC DESIGN CONSISTENCY

Corresponding Author:

David Llopis-Castelló
PhD Candidate
Highway Engineering Research Group (HERG), Universitat Politècnica de València
Camino de Vera, s/n – 46022, Valencia, Spain
Tel: (34) 96 3877374
E-mail: dallocas@doctor.upv.es

Other Authors:

Francesco Bella
Associate Professor
Roma Tre University, Department of Engineering
Via Vito Volterra, 62 – 00146 Rome, Italy
E-mail: francesco.bella@uniroma3.it

Francisco Javier Camacho-Torregrosa
Assistant Professor
HERG, Universitat Politècnica de València
E-mail: fracator@tra.upv.es

Alfredo García
Professor
HERG, Universitat Politècnica de València
E-mail: agarciag@tra.upv.es

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ABSTRACT

Road crashes are mainly caused by three concurrent factors: infrastructure, vehicle, and human factor. The interaction between infrastructure and human factor leads to the concept of geometric design consistency.

Recently, a global consistency model was developed based on the difference between the inertial operating speed profile and the operating speed profile. The first one was defined as the weighted average speed of the previous road section based on distance and represents drivers' expectancies, whereas the second one represents road behavior. However, drivers' expectancies are related to Short-Term Memory which is gradually in decline and depends on time. Thus, a time-based inertial operating speed would allow a more accurate estimation of the phenomenon.

This research analyzes different periods of time and weighting distributions to identify how drivers' expectancies should be estimated.

A set of 71 homogeneous road segments located in Italy were considered in the study. As a result, 25 seconds and a convex parabolic distribution should be used to calculate the inertial operating speed profile. This new way to estimate drivers' expectancies showed better results than those obtained based on distance.

Finally, the proposed consistency model was compared with the previous ones. As a conclusion, this model could more accurately assess the geometric design consistency. Therefore, the proposed consistency model is a useful tool for engineers to estimate the number of crashes and incorporate road safety to the geometric design of both new two-lane rural roads and improvements of existing highways.

Keywords: *geometric design consistency, road safety, operating speed, inertial operating speed, driver's behavior*

INTRODUCTION

Road safety is a major concern in our society. Around 1.2 million people die and 50 million are injured in road crashes every year (*1*). Most fatalities occur on rural roads. Specifically in Italy, 48% of all road crashes took place on these highways between 2011 and 2013 (*2*).

Road crashes are mainly caused by three concurrent factors: infrastructure, vehicle and human factor. Particularly, the infrastructure factor is responsible for over 30% of road crashes (*3*). In fact, crashes tend to concentrate at certain road elements. This is why the interaction between the infrastructure and the human factor have been deeply studied in recent years. This interaction can be partially explained using the concept of geometric design consistency, which can be defined as how road behavior meets drivers' expectancies. To this regard, a consistent road minimizes surprises to road users while driving along it, whereas an inconsistent road presents numerous surprises on drivers, leading to anomalous behavior and increasing the likelihood of crash occurrence.

There are several methods to assess geometric design consistency: operating speed, vehicle stability, alignment indices, and driver workload (*4*). However, most of the consistency models are based on the analysis of the operating speed profile. Operating speed is frequently defined as the 85th percentile of the speed distribution for passenger cars under free-flow conditions with no external restrictions (V_{85}). One important advantage of its use is the possibility to estimate them using operating speed models.

There are two types of consistency models: local and global. Local models focus on localized issues, such as sudden speed reductions or high differences between the design and operating speeds. Those models are ideal to identify where road crashes are more likely to take place. On the other hand, global consistency models examine the overall speed variation throughout an entire road segment. Although they do not indicate where crashes are likely to take place, they can be introduced into Safety Performance Function (SPF) to predict the number of crashes on an entire road segment.

The first global consistency model was developed by Polus and Mattar-Habib (*5*). In this research, two parameters to estimate geometric design consistency were proposed: relative area (R_a) and operating speed dispersion (σ). The first parameter was defined as the area bounded by the operating speed profile and the average operating speed, divided by the length of the road segment. Hence, higher values of R_a and σ produced lower consistency values. This model was later enhanced by including the speed dispersion induced by heavy vehicles, as a surrogate measure for the vertical alignment (*6*).

Related to this, Garach et al. (*7*) developed a new consistency model based on the same parameters in Spain. As a result, the Polus and Mattar-Habib's model showed a quite conservative behavior, since some road sections were classified as poor according to the global model, while presenting fair consistency according to R_a and σ.

Finally, Camacho-Torregrosa (*8*) developed another global consistency model considering two operational parameters: the average operating speed and the average deceleration rate. Additionally, this study highlights the importance of using homogeneous road segments. The author also presents a classification of road segments attending to their 'boundary constraints', i.e., the conditions at which road segments are connected to the rest of the road network. Several SPFs were developed accordingly.

Recently, Garach et al. (*9*) calibrated different SPFs considering different geometric, operating, and consistency variables. Among those consistency models presented above, the model which more accurately estimated the number of crashes on Spanish two-lane rural roads was that proposed by Camacho-Torregrosa. Likewise, the average operating speed also had an important influence on crash occurrence, with more crashes as the average operating speed increases.

Additionally, there are several authors who have studied the influence of the geometric design consistency on road safety (*10–17*). All of them concluded that there is a close relationship between consistency and road crashes. Regarding this, the operating speed reduction and the deviation of the operating speed along a road segment were identified as the most important variables. Furthermore, the selection of the road is critical for the application of global consistency models. The road segments must be homogeneous, since the length along which the *a priori* expectancies of drivers are acquired plays a major role (*8*, *13*, *18*).

However, none of the previous consistency models included the definition of the 'expectancies acquisition process' phenomenon in their formulation. Regarding this, García et al. (*19*) developed a novel approach at calculating drivers' expectancies and behavior. A new speed concept, the inertial operating speed (V_i), was proposed to estimate drivers' expectancies at a certain location. This speed was defined as the average operating speed of the previous 1,000 m road segment. This distance was determined with a naïve comparison to crash rates. Conversely, road behavior was associated with the operating speed (V_{85}). The Inertial Consistency Index (ICI) was defined as the difference between V_i and V_{85}. Therefore, the greater this index, the greater the difference between drivers' expectancies and road behavior, and thus crash occurrence is higher.

This inertial operating speed was also studied by Montella et al. (*16*) on motorways. Traditionally, this speed has been based on distance, considering different lengths and extracting a simple average. However, this does not match the drivers' expectation acquisition process, which is related to Short-Term Memory (STM).

STM is the memory system that contains our moment-to-moment conscious thoughts and perceptions. The capacity of STM increases with a person's age until it reaches a maximum in young adulthood. As long as we are able to rehearse, or pay attention to the information in STM, it can reside there indefinitely. However, without rehearsal, STM is gradually in decline and the information is lost in about 18 s (*20*).

Drivers do not recall with the same intensity the previous road section. Therefore, the initial and final zones of the preceding section should not be equally considered when determining the inertial operating speed. To this regard, Llopis-Castelló et al. (*21*) defined V_i as the weighted average operating speed based on distance to develop a new global consistency model based on the difference between the inertial operating speed profile and the operating speed profile. As expected, this way of calculating V_i showed better results than estimating this speed as the simple average of the operating speed. However, given two homogeneous road segments with a different average operating speed, the periods of time needed to cover the same distance differ. Thus, a time-based inertial operating speed profile determination might lead to a more reliable estimation of the phenomenon.

This paper shows the analysis of different periods of time and weighting distributions in the calculation of the inertial operating speed to identify how drivers' expectancies should be estimated and, consequently, enhance the assessment of the geometric design consistency.

OBJECTIVES AND HYPOTHESES

The main objective of this research is to determinate how the inertial operating speed (V_i) should be calculated to estimate in a more accurate way drivers' expectancies. The period of time needed to accurately reflect these expectancies into V_i remains unknown, so different trials will be performed using different periods of time, comparing their difference with V_{85} towards the number of crashes.

The underlying hypothesis is that the inertial operating speed profile based on time will allow a more accurate estimation of the number of crashes than the distance-based one. In addition, weighted averages will be used for this determination to achieve a more reliable measure of driver expectancies. The difference between V_i and V_{85} will be considered as a surrogate measure to geometric design consistency. Then, the higher the difference between V_i and V_{85}, the lower the consistency.

METHODOLOGY AND DATA DESCRIPTION

Methodology

This study was developed by examining the relationship between the operating speed behavior and road crashes. Different two-lane rural road sections located in Italy were selected. Next, the geometry for each road section was recreated by means of the methodology proposed by Camacho-Torregrosa et al. (*22*); and the operating speed profiles were estimated considering the speed models calibrated by Marchionna and Perco (*23*). From this, different inertial operating speed profiles were calculated for each homogeneous road segment considering different periods of time and weighting distributions. Crash and traffic data were also obtained. Finally, the relationship between crashes and consistency was studied by calibrating several Safety Performance Functions. As a result, the inertial operating speed profile that better describes drivers' expectancies was identified and consistency thresholds were proposed.

Road segments

A total of 48 road sections located in Italy were selected for the study. These resulted in 71 homogeneous road segments, which were identified through the following procedure.

First, road segments were divided into sections with similar traffic volume and cross-section. Major intersections do also influence on drivers' expectancies, so they were considered for segmentation. Finally, each road section was divided according to its geometric behavior using the Curvature Change Rate (*CCR*), which is defined as the rate between the sum of the absolute deflection angles per length unit.

The homogeneous road segments had an Annual Average Daily Traffic (*AADT*) volumes ranging from 1,319 to 19,577 vpd. Their length ranged from 1,915 m to 19,325 m, and their longitudinal grade did not exceed 5%. Lane width ranged from 3.00 to 3.50 m, and the shoulder width varied from 0.50 to 1.50 m.

Traffic and crash data

Traffic volume and crash data were provided by the "Azienda Nazionale Autonoma delle Strade" (ANAS) and the "Automobile Club Italia" (ACI), respectively. Thus, *AADT* and the number of crashes with injuries were identified for each homogeneous road segment.

AADT was defined as the average traffic volume from 2012 to 2015. Only crashes with injuries were considered between 2005 and 2014. The cause of every crash was reviewed, so to only include the ones related to geometry (e.g., crashes caused by vehicles entering the road from minor roads or driveways were removed from the analysis, since their inception is not the road geometry per se). As a result, a total of 2,080 crashes were reported, involving 202 fatalities and 3,701 injured.

Speed profiles

Operating speed profiles

The operating speed profile for each road segment was estimated using the model by Marchionna and Perco (*23*) for Italian two-lane rural roads (Figure 1). The model takes into account the general character of the horizontal alignment, since the desired speed is calculated as a function of the *CCR*.

Inertial speed profiles

The inertial operating speed profile was calculated for every road segment from its operating speed profile. This speed attempts to define drivers' expectancies, which are related to the short-term memory. As said above, this memory depends on time and is gradually in decline (*20*).

Therefore, the inertial operating speed for each point of the alignment was defined as the weighted average operating speed of the preceding road section.

The time for which the inertial operating speed should be calculated was unknown, so periods of time (*t*) between 10 s and 60 s with a step of 5 s and four weighting distributions were analyzed (Figure 2).

A constant distribution provides the average speed, since the operating speed for all different stations under consideration has the same weight. To calculate the other distributions, a weighting factor was proposed, ranging from 0 to 1. Except for the constant distribution, the weighting factor is always 0 for the furthest point, and 1 for the closest one. In addition, the vertexes of the convex and concave parabolic distributions were in 1 and 0, respectively. The equations of these distributions are shown in Figure 2, where s_j is the actual station in meters, w_j is the weighting factor in this station and s_o and s_f are the initial and final station in meters.

It is worth to highlight that the distance (s_f - s_o) to consider for every inertial speed calculation varies along the road, as a function of the speed. For instance, a road segment in which there are two stations presenting an operating speed of 40 km/h and 70 km/h will compute the inertial operating speed using different distances, being longest the one for 70 km/h.

The inertial operating speed is thus determined as the weighted average speed of the last *t* seconds according to the weighting distribution:

$$\boldsymbol{V_{i,k}} = \frac{\sum \boldsymbol{w_j} \cdot \boldsymbol{V_{85,j}}}{\sum \boldsymbol{w_j}} \qquad (1)$$

where $V_{i,k}$: inertial operating speed (km/h) at the point *k*; $V_{85,j}$: operating speed at the point *j*; and w_j: weighting factor at the point *j*.

As a result, 44 (11 periods of time x 4 weighting distributions) inertial operating speed profiles were developed for each road segment. Figure 1 shows V_{85} and V_i for one of the road segments under study in forward direction, considering 25 s and a convex parabolic distribution.

Consistency parameters

Different consistency parameters were proposed considering several variables based on the difference between V_i and V_{85} (*21*). Figure 3 shows the speed differences between the speed profiles depicted in Figure 1. According to this definition, a positive speed difference means that drivers' expectancies are violated, since drivers' speed is lower than the speed they expect to reach. The likelihood of crashes increases with the magnitude of these differences.

The consistency parameters will be composed as a combination of the following, simple parameters (Figure 3):

- *A* (m·km/h): area bounded by the difference between V_i and V_{85}, and the x axis.
- *L* (m): length of the road segment.
- σ (km/h): standard deviation of the difference between V_i and V_{85}.
- *A(+)* (m·km/h): area bounded by the difference between V_i and V_{85} considering only the positive differences.

- *L(+)* (m): length of the road segment considering only the positive differences.
- *σ(+)* (km/h): standard deviation of the difference between V_i and V_{85} considering only the positive differences.
- *A(> x km/h)* (m·km/h): area bounded when the difference between V_i and V_{85} is higher than x km/h.

A higher value for either of these variables (dispersion or area bounded) will lead to a lower consistency. This will make it a little bit easier the interpretation of the final consistency parameter.

Table 1 summarizes the proposed consistency parameters (*21*). All parameters are expressed in terms of speed. This easy interpretation of the consistency parameter is an advantage compared to other consistency models. In all cases, a higher value of the parameter indicates a lower consistency level.

RESULTS

The best consistency parameter was identified by examining its relationship to road crashes. Following common practice, generalized linear modelling techniques were used to fit a Safety Performance Function that relates exposure and consistency to the number of crashes (Equation 2). A negative binomial distribution was assumed, since it is an appropriate solution with overdispersed, count data (*24*).

$$\boldsymbol{Y_{i,10} = e^{\beta_0} \cdot L^{\beta_1} \cdot AADT^{\beta_2} \cdot e^{\beta_3 \cdot C}} \quad (2)$$

where $Y_{i,10}$: crashes with injuries on the road segment in 10 years; β_i: regression coefficients; *L*: length of the road segment (km); *AADT*: Average Annual Daily Traffic (vpd); and *C*: consistency parameter (km/h).

The *AIC* (Akaike Information Criterion) was given for all regressions as a measure of goodness of fit. The smaller the *AIC* value, the better the model.

The quality of fit was also studied from the Cumulative Residuals (CURE) Plots (*25*, *26*). This method consists of plotting the cumulative residuals for each independent variable. The aim is to graphically observe how well the function fits the data set. The CURE method has the advantage of not being dependent on the number of observations, as are many other traditional statistical procedures. In general, a good cumulative residuals plot is one that oscillates around 0. Thus, a good fit is given when the residuals do not stray beyond the ±2σ* boundaries.

Exposure influence

It is well known that crashes are highly affected by the exposure. Indeed, several previous researchers have developed safety performance functions that only depend on the exposure (*13*, *27*). A Safety Performance Function that only considers exposure was calibrated (Equation 3).

$$\boldsymbol{Y_{i,10} = e^{-7.2212} \cdot L^{0.7070} \cdot AADT^{1.0307} \qquad AIC = 557.92} \quad (3)$$

This model is not of major interest, but is useful to determine how important the inclusion of the consistency term is for crash estimation. As expected, all parameters are statistically significant. The *AADT* estimate is close to 1, indicating that the number of crashes is linearly affected by the traffic volume under consideration. On the other hand, the length estimate is lower than 1, so longer homogeneous road segments induce lower crash rates.

Consistency influence

A total of 352 Safety Performance Functions were calibrated by combining 44 inertial operating speed profile types and 8 consistency parameters.

All models were sorted as a function of their *AIC* value. In this regard, Table 2 shows the 25 models with the lowest *AIC* values. It can be noticed that parameter 7 was the most important.

This parameter includes the positive difference between the inertial operating speed and operating speed (Table 1). According to the inception of the inertial operating speed profile, the linear or parabolic weighting distributions produced the best results, validating the hypothesis that the last seconds have a major influence in drivers' expectancies, since the constant weighting distribution was not the best. As expected, the *AIC* values were lower than for the single-exposure SPF (*AIC*=557.92).

The evolution of the *AIC* for every SPF was also analyzed according to every parameter and weighting distribution. The objective was to examine the sensitivity of the SPF to the type of consistency parameter. Figure 4 shows the trend of the *AIC* value considering the parameter 7 and the convex parabolic distribution. To this regard, the period of time between 20 and 30 seconds was identified for all weighting distributions and consistency parameters as the best. This value is in accordance with previous research.

The lowest *AIC* value was found for 25 s and the consistency parameter 7 (model 25PX7, where PX indicates a convex parabolic distribution). The corresponding SPF is:

$$Y_{i,10} = e^{-8.57584} \cdot L^{1.03083} \cdot AADT^{1.02707} \cdot e^{0.17098 \cdot C} \qquad AIC = 547.01 \quad (4)$$

Finally, the model was validated by means of CURE plots (Figure 5). It can be observed that the plots against each explanatory variable do not stray beyond the ±2σ* boundaries, apart from a few points when the *AADT* or *C* are high. It is mainly due to the limited available data for large traffic volumes and road segments with very poor consistency. In these situations, the proposed model tends to underestimate the number of crashes. So, it is recommended to use the proposed consistency model for road segments which present a traffic volume lower than 13,500 vpd. Despite this, the consistency model is a useful tool to estimate the number of crashes in Italian two-lane rural roads.

DISCUSSION

Inertial operating speed

The inertial operating speed was defined as the weighted average operating speed based on time, which attempts to better reflect the behavior of the short-term memory (*20*), instead of considering the instant operating speed like other consistency models do. As a result, this speed should be calculated at each station as the weighted average operating speed for the last 25 seconds, according to a convex parabolic distribution.

It is important to highlight that V_i was calculated considering a certain period of time – and not a certain distance. This assumption makes sense, since the human mind tends to keep in mind information as a function of time, not of distance covered. In fact, the authors calculated V_i in terms of distance in a previous research (*21*), but time-based models shows a better goodness of fit (*AIC* of 547.01 vs. 548.15).

An additional advantage of considering time to calculate the inertial operating speed is its higher stability for different consistency parameters. All consistency parameters showed the minimum *AIC* values for 25 s, whereas the distance-based model presented their best results for a range of distances. This is not surprising, since different lengths can be reached in a same period of time depending on the speed.

Effect of the consistency parameter on road crashes

The proposed consistency parameter was parameter 7, which is defined considering only the positive differences between V_i and V_{85} (Table 1).

A positive difference between these speed profiles means that drivers' expectancies are violated. Therefore, a higher crash rate is expected. Thus, for a given *A(+)*, a higher length and a lower $\sigma(+)$ leads to a lower crash rate, i.e., a good consistency. Likewise, for a given $L(+)$, a higher $A(+)$ or $\sigma(+)$ leads to a higher crash rate, i.e., a poor consistency. These conclusions can be observed in Figure 6, where the volume of the circles depicts crash rates. In this figure, transparent circles are the projection of the red ones.

As a result, crash rates increase with the consistency parameter. In this way, different consistency thresholds were defined by means of a cluster analysis. Thus, the level of consistency of a homogenous road segment can be defined as good, fair or poor depending on the value of this consistency parameter (Figure 7).

Therefore, this consistency model can be used to compare and sort different design proposals, maximizing road safety. The proposed SPF (Equation 4) is a useful tool for engineers to estimate the number of crashes, and to determine the potential for improvement of a certain road solution, or set of solutions.

Comparison with previous global consistency models

The proposed consistency model was compared with the global consistency models developed by Polus and Mattar-Habib (*5*), Garach et al. (*7*) and Camacho-Torregrosa (*8*).

Different SPFs were calibrated considering the consistency parameters developed by these authors (Table 3). It can be observed that these models offered a worse statistical adjustment than the proposed model, since their *AIC* values were higher.

Additionally, the Root-Mean-Square Error (RMSE) and the Mean Absolute Error (MAE) were calculated for each model (Table 3). As a result, the proposed model showed slightly lower values than the previous models.

So, the consistency parameter of the enhanced consistency model can better represent the phenomenon than the previous models.

CONCLUSIONS

A more accurate way to estimate drivers' expectancies by means of the inertial operating speed profile has been proposed to enhance the assessment of geometric design consistency through the model proposed by Llopis-Castelló et al. (*21*). This model was defined through the difference between the inertial operating speed profile (V_i), which represents drivers' expectancies and the operating speed profile (V_{85}), which represents road behavior.

Different periods of time and weighting distributions were studied to identify how inertial operating speed should be calculated. For this, a total of 352 SPFs were calibrated. Most of them which incorporate a consistency parameter showed lower *AIC* values than the SPF considering only the exposure. So, the level of consistency significantly influences on crash occurrence.

The best model was 25PX7 model. To this regard, the inertial operating speed profile was estimated considering 25 seconds and a convex parabolic distribution. Likewise, the consistency parameter was obtained from the positive differences between V_i and V_{85}.

The proposed model was consistent with the short-term memory behavior. Regarding this, an inertial operating speed profile based on time can better represent drivers' expectancies than those profiles based on distance.

Finally, the proposed consistency model was compared with the previous ones. As a result, the developed model showed the lowest *AIC* value and a closer relationship with the observed crashes. Additionally, different thresholds were defined to identify the consistency level of a homogeneous road segment.

Therefore, the proposed global consistency model better describes the phenomenon than the previous ones. The new SPF is a useful tool for engineers to estimate the number of crashes and bring a more objective assessment of road safety to the geometric road design process.

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AUTHORS CONTRIBUTION

The authors confirm contribution to the paper as follows:

- Study conception and design: Llopis-Castelló, D., Camacho-Torregrosa, F.J. and García, A.
- Data collection: Llopis-Castelló, D. and Bella, F.
- Analysis and interpretation of results: Llopis-Castelló, D., Bella, F. and Camacho-Torregrosa, F.J.
- Draft manuscript preparation: Llopis-Castelló, D.

All authors reviewed the results and approved the final version of the manuscript.

REFERENCES

1. WHO. Global status report on road safety 2015. World Health Organization, 2015.
2. European Transport Safety Council. Ranking EU Progress on Improving Motorway Safety. PIN Flash Report, Vol. 28, No. March, 2015.
3. Treat, J. R., N. S. Tumbas, S. T. McDonald, D. Shinar, and R. D. Hume. Tri-level study of the causes of traffic accidents: Executive summary (National Technical Information Services Technical Report No. DOT HS-805 099). Bloomington: University of Indiana, 1979.
4. Gibreel, G. M., S. M. Easa, Y. Hassan, and I. A. El-Dimeery. State of the art of highway geometric design consistency. Journal of Transportation Engineering, 1999, vol. 125, no 4, p. 305-313.
5. Polus, A., and C. Mattar-Habib. New consistency model for rural highways and its relationship to safety. Journal of transportation engineering, 2004, vol. 130, no 3, p. 286-293.
6. Mattar-Habib, C., A. Polus, and H. Farah. Further evaluation of the relationship between enhanced consistency model and safety of two-lane rural roads in Israel and Germany. European Journal of Transport and Infrastructure Research, 2008, vol. 4, no 8.
7. Garach, L., F. Calvo, M. Pasadas, and J. de Oña. Proposal of a New Global Model of Consistency: Application in Two-Lane Rural Highways in Spain. Journal of Transportation Engineering, 2014, vol. 140, no 8, p. 04014030.
8. Camacho Torregrosa, F. J. Development and calibration of a global geometric design consistency model for two-lane rural highways, based on the use of continuous operating speed profiles. Universitat Politècnica de València, Valencia (Spain), 2015.
9. Garach, L., J. de Oña, G. López, and L. Baena. Development of safety performance functions for Spanish two-lane rural highways on flat terrain. Accident Analysis & Prevention, 2016, vol. 95, p. 250-265.
10. Anderson, I., K. Bauer, and D. Harwood. Relationship to safety of geometric design consistency measures for rural two-lane highways. Transportation Research Record: Journal of the Transportation Research Board, 1999, no 1658, p. 43-51.
11. Ng, J., and T. Sayed. Effect of geometric design consistency on road safety. Canadian Journal of Civil Engineering, 2004, vol. 31, no 2, p. 218-227.
12. Awatta, M., Y. Hassan, and T. Sayed. Quantitative evaluation of highway safety performance based on design consistency. Advances in Transportation Studies, 2006, vol. 9.
13. Cafiso, S., A. Di Graziano, G. Di Silvestro, G. La Cava, and B. Persaud. Development of comprehensive accident models for two-lane rural highways using exposure, geometry, consistency and context variables. Accident Analysis & Prevention, 2010, vol. 42, no 4, p. 1072-1079.
14. Quddus, M. Exploring the relationship between average speed, speed variation, and accident rates using spatial statistical models and GIS. Journal of Transportation Safety & Security, 2013, vol. 5, no 1, p. 27-45.
15. Montella, A., L. Colantuoni, and R. Lamberti. Crash prediction models for rural motorways. Transportation Research Record: Journal of the Transportation Research Board, 2008, no 2083, p. 180-189.

16. Montella, A., and L. L. Imbriani. Safety performance functions incorporating design consistency variables. Accident Analysis & Prevention, 2015, vol. 74, p. 133-144.
17. Wu, K.-F., E. T. Donnell, S. C. Himes, and L. Sasidharan. Exploring the association between traffic safety and geometric design consistency based on vehicle speed metrics. Journal of Transportation Engineering, 2013, vol. 139, no 7, p. 738-748.
18. Resende, P., and R. Benekohal. Effect of roadway section length on accident modeling traffic congestion and traffic safety. The 21 st Century Conference, ASCE, Chicago, IL. 1997.
19. García, A., D. Llopis-Castelló, F. J. Camacho-Torregrosa, and A. M. Pérez-Zuriaga. New consistency index based on inertial operating speed. Transportation Research Record: Journal of the Transportation Research Board, 2013, no 2391, p. 105-112.
20. Revlin, R. Cognition: Theory and practice. Palgrave Macmillan, 2012.
21. Llopis-Castelló, D., F. Bella, F. J. Camacho-Torregrosa, and A. García. New consistency model based on inertial operating speed profiles for road safety evaluation. Journal of Transportation Engineering, Accepted, 2017.
22. Camacho-Torregrosa, F. J., A. M. Pérez-Zuriaga, J. M. Campoy-Ungría, A. García, and A. P. Tarko. Use of Heading Direction for Recreating the Horizontal Alignment of an Existing Road. Computer-Aided Civil and Infrastructure Engineering, 2015, vol. 30, no 4, p. 282-299.
23. Marchionna, A., and Perco, P. Operating speed-profile prediction model for two-lane rural roads in the Italian context. Advances in transportation studies, 2008, vol. 2008, no 14, p. 57-68.
24. Lord, D., and F. Mannering. The statistical analysis of crash-frequency data: a review and assessment of methodological alternatives. Transportation Research Part A: Policy and Practice, 2010, vol. 44, no 5, p. 291-305.
25. Hauer, E., and J. Bamfo. Two tools for finding what function links the dependent variable to the explanatory variables. Proceedings of the ICTCT 1997 Conference, Lund, Sweden. 1997.
26. Lord, D., and B. N. Persaud. Accident prediction models with and without trend: application of the generalized estimating equations procedure. Transportation Research Record: Journal of the Transportation Research Board, 2000, no 1717, p. 102-108.
27. Harwood, D., F. Council, E. Hauer, and W. Hughes. Prediction of the expected safety performance of rural two-lane highways. 2000.

LIST OF FIGURE CAPTIONS:

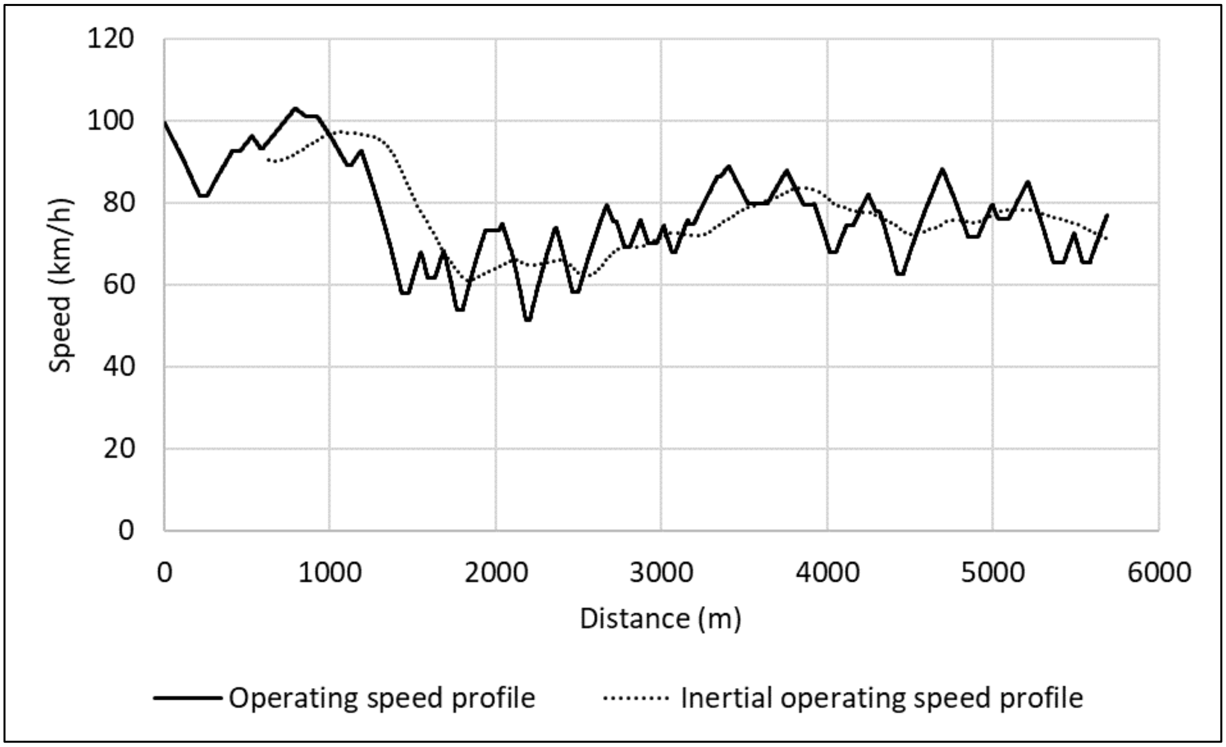
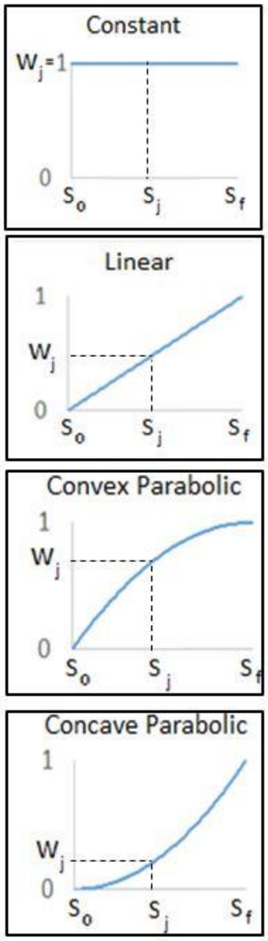


FIGURE 1 Speed profiles.



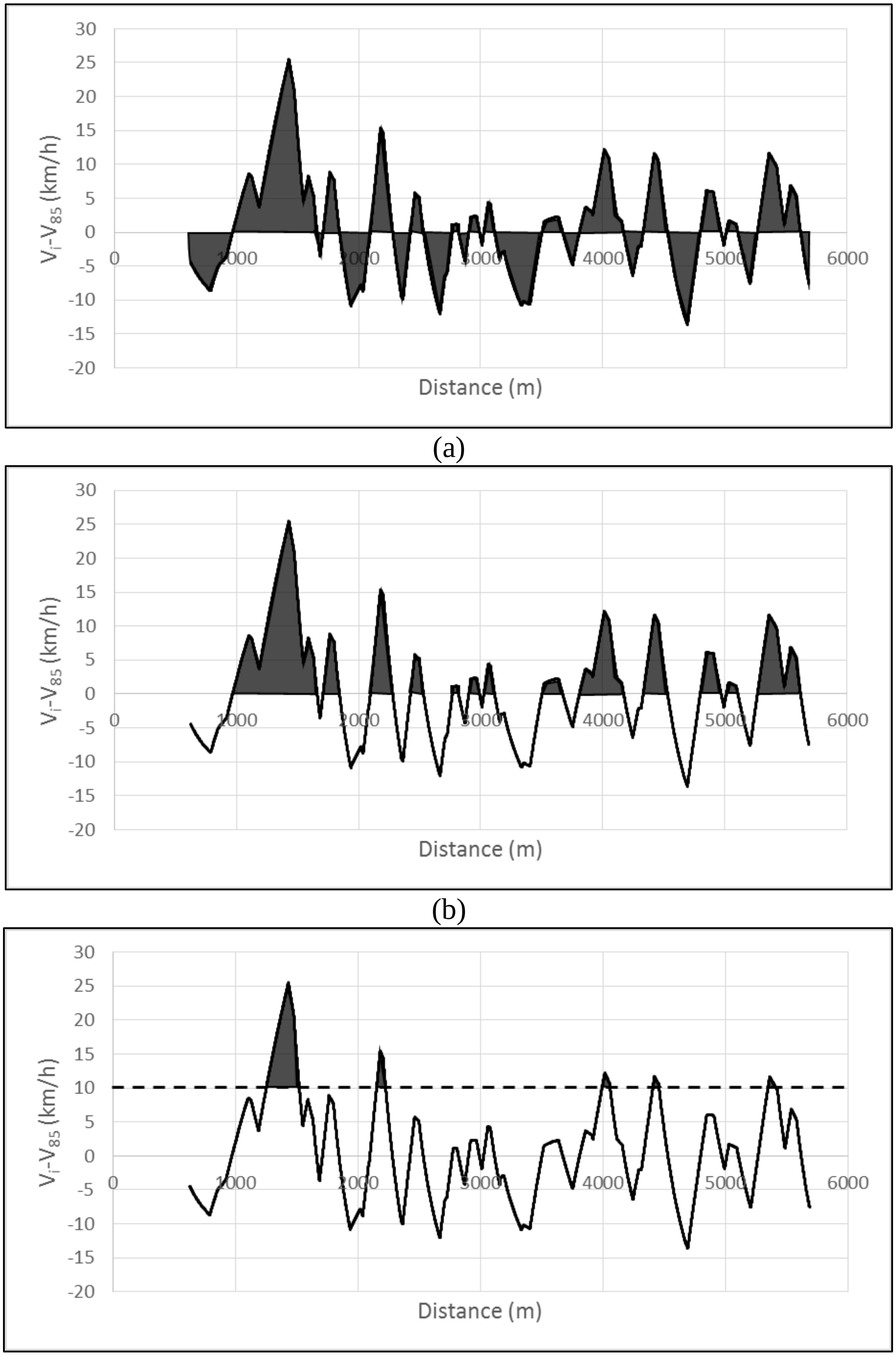
$$w_j = 1$$

$$w_j = \frac{(s_j - s_o)}{(s_f - s_o)}$$

$$w_j = -\frac{(s_j - s_o)^2}{(s_f - s_o)^2} + \frac{2 \cdot (s_j - s_o)}{(s_f - s_o)}$$

$$w_j = \frac{(s_j - s_o)^2}{(s_f - s_o)^2}$$

FIGURE 2 Weighting distributions.

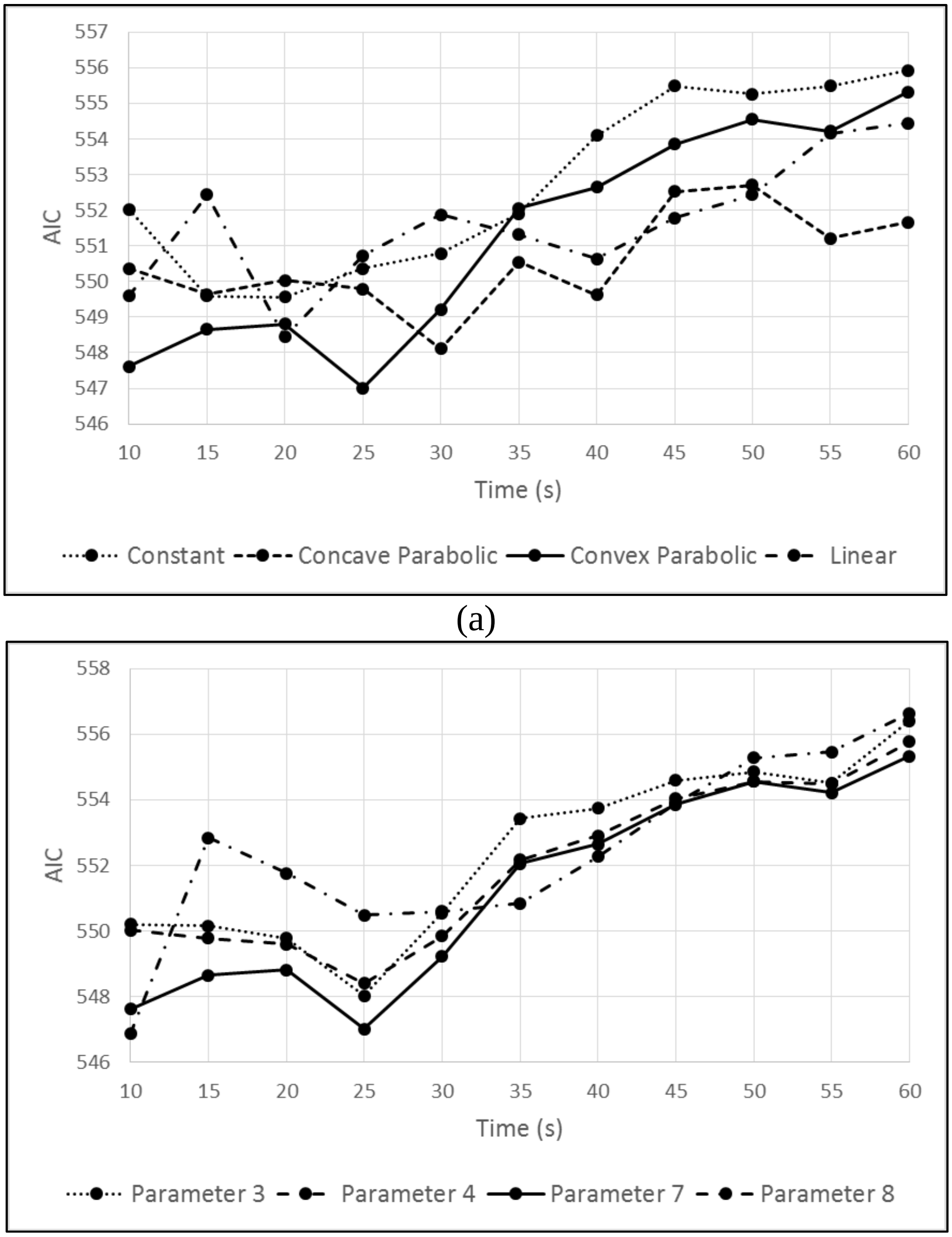


(a)

(b)

(c)

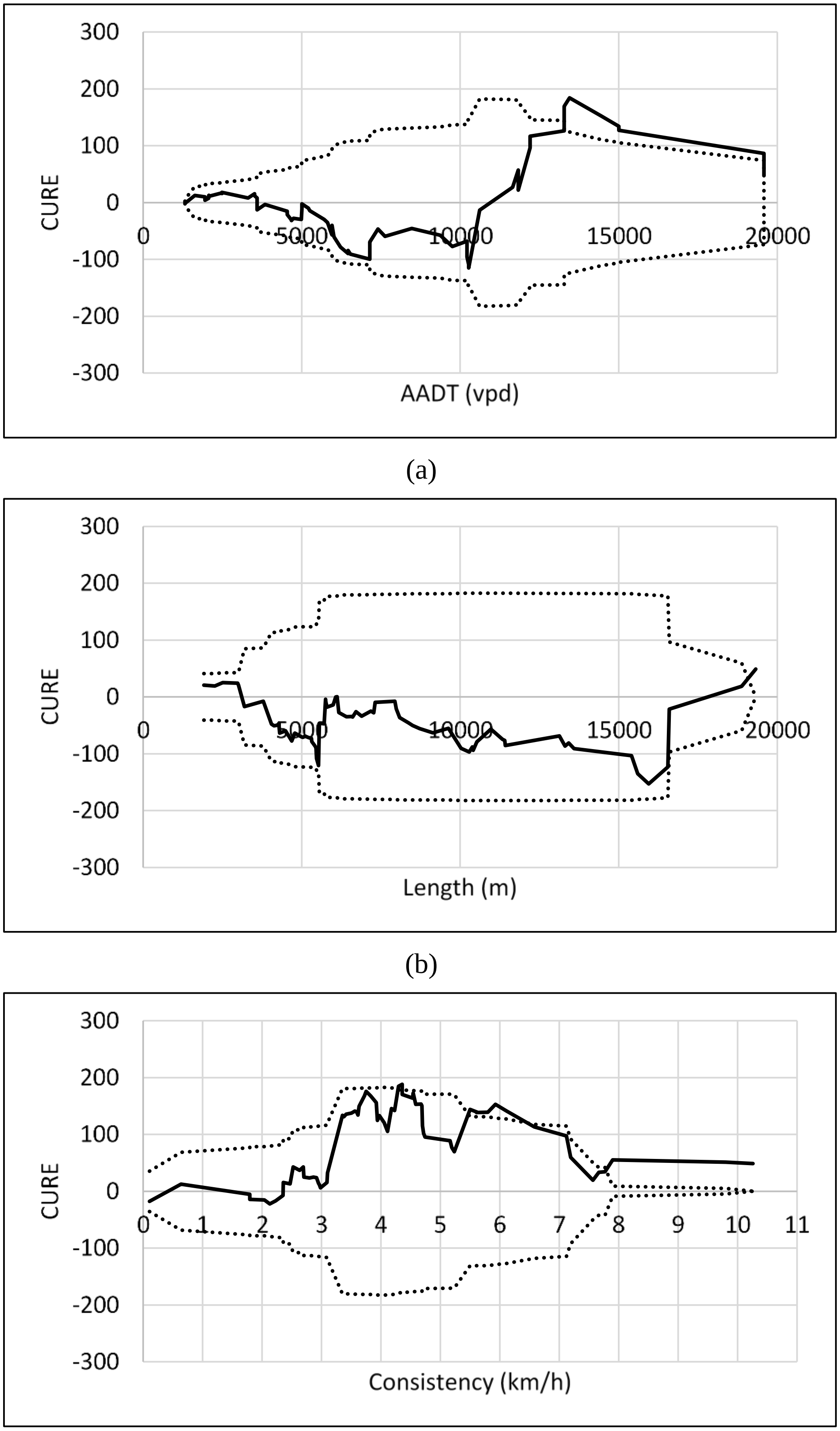
FIGURE 3 Consistency variables: (a) *A*, *L* and *σ*; (b) *A(+)*, *L(+)* and *σ(+)*; and (c) *A(> x km/h)*.



(a)

(b)

FIGURE 4 Evolution of the *AIC* value: (a) Consistency parameter 7; (b) Convex parabolic distribution.



(a)

(b)

(c)

FIGURE 5 CURE plots: (a) *AADT*; (b) Length; (c) Consistency.

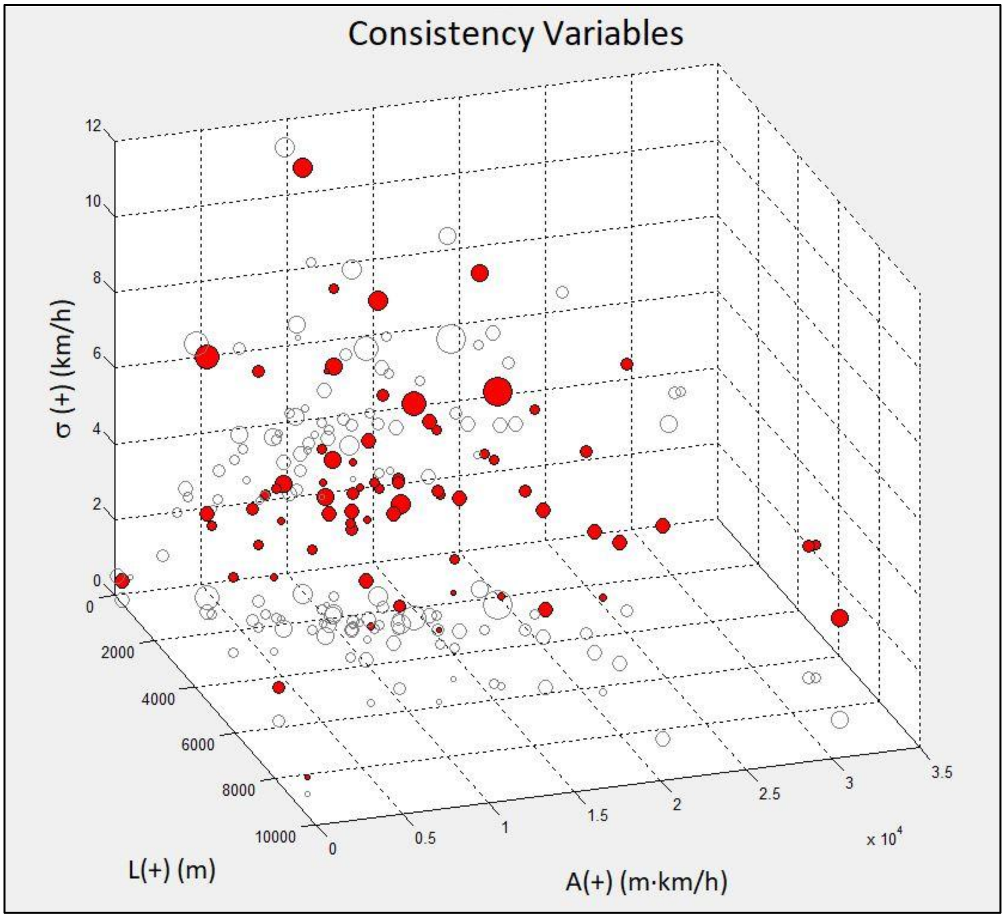
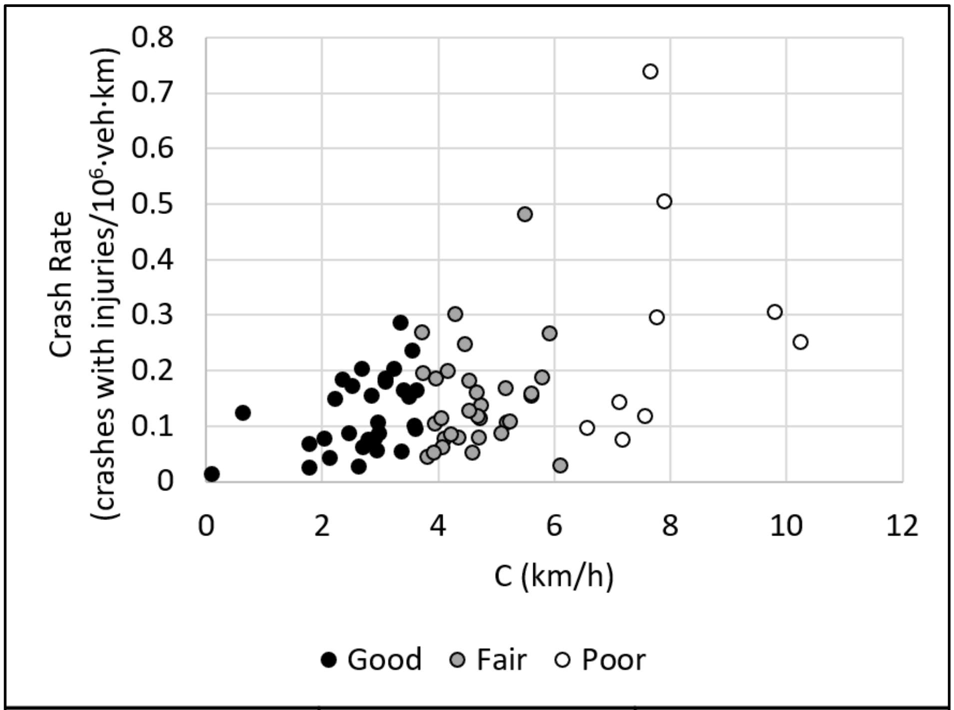


FIGURE 6 Relationship between consistency variables and crash rate.



Good	Fair	Poor
C ≤ 3.65 km/h	3.65 < C ≤ 6.5 km/h	C > 6.5 km/h

FIGURE 7 Relationship between the crash rate and the consistency parameter.

LIST OF TABLES:

TABLE 1 Consistency parameter

Consistency parameter	Equation
1	$\sqrt{\frac{A(+)\cdot\sigma}{L}}\ [km/h]$
2	$\sqrt{\frac{A\cdot\sigma}{L}}\,[km/h]$
3	$\frac{A(+)}{L(+)}\,[km/h]$
4	$\frac{A(>10\ km/h)}{L}\,[km/h]$
5	$\frac{A(>15\ km/h)}{L}\,[km/h]$
6	$\frac{A(>20\ km/h)}{L}\,[km/h]$
7	$\sqrt{\frac{A(+)\cdot\sigma(+)}{L(+)}}\ [km/h]$
8	$\sqrt{\frac{A(+)\cdot\sigma}{L(+)}}\ [km/h]$

TABLE 2 Ranking of the models according to the *AIC* value

Model	Parameter	Time (s)	Weighting distribution	*AIC*
10PX4	Parameter 4	10	Convex	546.87
25PX7	Parameter 7	25	Convex	547.01
10PX7	Parameter 7	10	Convex	547.62
10L4	Parameter 4	10	Linear	547.77
25PX3	Parameter 3	25	Convex	548.02
30PV7	Parameter 7	30	Concave	548.12
25PX8	Parameter 8	25	Convex	548.4
20L7	Parameter 7	20	Linear	548.44
30PV3	Parameter 3	30	Concave	548.46
30PV8	Parameter 8	30	Concave	548.48
15PX7	Parameter 7	15	Convex	548.65
20PX7	Parameter 7	20	Convex	548.81
20L3	Parameter 3	20	Linear	549
10C5	Parameter 5	10	Constant	549.01
30PX7	Parameter 7	30	Convex	549.22
20L8	Parameter 8	20	Linear	549.23
30PV1	Parameter 1	30	Concave	549.3
20C7	Parameter 7	20	Constant	549.56
10L7	Parameter 7	10	Linear	549.59
30L1	Parameter 1	30	Linear	549.6
15C7	Parameter 7	15	Constant	549.6
20PX8	Parameter 8	20	Convex	549.6
40PV7	Parameter 7	40	Concave	549.62
15PV7	Parameter 7	15	Concave	549.64
20PX3	Parameter 3	20	Convex	549.78

TABLE 3 Statistical adjustment – Global consistency models

		β_0	**β_1**	**β_2**	**β_3**	***AIC***	**α**	**RMSE**	**MAE**
		-	**ln *L***	**ln *AADT***	***C***				
Polus and Mattar-Habib	Estimate	-6.95815	0.9458	0.9929	-0.3352	553.48	0.3174	22.43	14.03
	Pr(>|z|)	$< 2\cdot10^{-16}$	$4.26\cdot10^{-8}$	$< 2\cdot10^{-16}$	0.00943				
Garach et al.	Estimate	-7.08048	0.9050	1.0146	-0.2917	554.87	0.3247	23.03	14.10
	Pr(>|z|)	$< 2\cdot10^{-16}$	$9.58\cdot10^{-8}$	$< 2\cdot10^{-16}$	0.0169				
Camacho-Torregrosa	Estimate	-6.77612	0.9206	1.0335	-0.2221	555.75	0.3254	21.88	14.10
	Pr(>|z|)	$5.21\cdot10^{-16}$	$1.94\cdot10^{-7}$	$< 2\cdot10^{-16}$	0.0379				
New model	Estimate	-8.57584	1.03083	1.02707	0.17098	547.01	0.287	21.64	13.75
	Pr(>|z|)	$< 2\cdot10^{-16}$	$2.28\cdot10^{-10}$	$< 2\cdot10^{-16}$	0.00015				