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DESIGN CONSISTENCY INDEX FOR TWO-LANE ROADS BASED ON CONTINUOUS SPEED PROFILES

ABSTRACT

It is well known that road accidents tend to be more frequent in locations where a sudden change in road characteristics violates the driver's expectations. Most methods used to assess the design consistency are based on simplified speed profiles that give a coarse description of the vehicle dynamics along the road. This paper presents a new approach to quantify the road design consistency, based on continuous operating speed profiles. These profiles are based on the Gipps' car-following equations, adapted to simulate the driver behaviour in the vicinity of horizontal curves under free-flow conditions. A methodology to calibrate and validate the Gipps' behavioural parameters from field data is presented and applied to predict the speed profiles of three drivers for a set of rural road segments. The calibration is based on trajectory data collected with an instrumented vehicle and it follows an automated procedure that aims to minimize the differences between the predicted and observed speed profiles. The new consistency index is based on the deceleration distances and it allows to overcome some limitations of the existing methods.

KEY WORDS

design consistency; speed profiles; road safety; operating speed; acceleration; deceleration; Gipps;

1. INTRODUCTION

The concept of design speed is used in most manuals to define the minimum road geometric design parameters [1]. Concerning the safety of horizontal curves, this concept does not ensure a road design that conforms to the natural expectations of the drivers, revealing itself simultaneously inadequate and overly limitative. Therefore, the concept of geometric design consistency was defined as a way to prevent sudden changes on geometrical features of contiguous road elements and the use of combinations of elements that do not comply with the driver's expectations.

In the past few decades, speed has been one of the main focuses of attention from researchers of many countries, resulting in numerous operating speed models [2, 3]. The operating speed is the most frequently used criterion to evaluate road design consistency and it is frequently estimated by the 85th percentile of the speed distribution observed in real driving conditions [4]. In the same way, the Highway Capacity Manual (HCM) [5] denotes speed as the most adequate parameter to ensure an economical and environmental analysis regarding two-lane rural highways.

Several models have been developed to estimate the operating speed in curves [6-8]. The horizontal alignment geometry has been referred to as the most restrictive factor when estimating the operating speed, and various parameters are used, e.g. curve radius (R), degree of curvature, curvature change rate (CCR), or simply the curvature (1/R) [6, 7, 9]. Other factors include speed limit, number of lanes, road classification, heavy vehicles percentage, weather conditions, sight distances, time of day, and driver behaviour characteristics [10, 11].

The procedure of collecting data in most of these cases consists of measuring the vehicles' instant speed at fixed sections using portable equipment (e.g. speed guns, microwave detectors, or pneumatic tubes). Usually, this results in a substantial amount of data that allows a precise characterization of the speed distribution at those sections. However, this method has two main limitations: i) it provides speed information only for a limited set of sections; b) it does not reveal how individual drivers adjust their speed from the approach to the curve exit. Consequently, the operating speed models that are based on spot-speed data require several assumptions, such as constant speed along the circular curves and constant deceleration and acceleration values. For example, the model developed by Lamm et al. [12] uses the CCR variable as the only explanatory variable for estimating the operating speed in curves, and assumes that the acceleration and deceleration occur only at the tangent, and is equal to ±0.85 m/s2. Similar values are considered by the present Portuguese design manual (±0.80 m/s^2).

As mentioned, it is important to define road designs that do not impose significant deviations to the geometrical characteristics of consecutive road elements and by inherency abrupt changes in driver behaviour [13, 14]. The need to predict driver behaviour in these particular situations have resulted in several methods to evaluate standard geometric design consistency of two-lane rural highways.

A simpler approach to evaluate the design consistency is by means of using alignment indices [15]. These geometric indices, e.g. the average radius (AR), the ratio between the maximum and minimum radius (RR), and the ratio of the curve radius to the average radius of the entire segment (CRR), can be used to evaluate the design consistency and to identify discontinuity areas of the road. Other methods have been used to model the driver workload and to measure the effect that design consistency has over this parameter. The study developed by Krammes et al. [16] used a method comprising vision occlusion to determine the driver workload in horizontal curves, concluding that it increases linearly as the degree of the curvature increases. Still, driver workload is much less used than other methodologies because of its higher degree of measurement difficulty. An alternative approach that has been used to evaluate design consistency in single geometric elements of the road is the analysis of the vehicle stability which compares the side friction provided by the curve and the side friction demanded by vehicles. Driving simulators have also been used to identify geometric inconsistencies [17].

Considering several limitations of the previous methods, Lamm et al. [12] developed the method that is normally used to evaluate design consistency. It consists in two design consistency criteria related to operating speed, which include the difference between design speed and operating speed, and the difference between operating speeds on contiguous elements of the road. This principle can be extended to the entire road segment using continuous speed profiles [18, 19].

Currently, it is well accepted that the estimation of the speed profile is a fundamental step to evaluate the design consistency of a road. This way, the objective of this research is to develop a new geometric design consistency evaluation methodology for two-lane rural highways, primarily based on continuous speed profiles predicted by a car-following model. Speed data are collected with an instrumented vehicle to develop, calibrate and validate a model that predicts speed profiles for individual drivers. In contrast with spot-speed measurements, the continuous acquisition system allows studying more extensively the behaviour of the driver, specifically the operating speed differential along the geometrical elements of the road, and also observing where and when the speed transition point occurs. This model assumes free-flow conditions. This is the most demanding scenario, as drivers are allowed to accelerate to their desired speed on the tangent sections, thus requiring the adoption of abnormally high deceleration rates or deceleration distances when approaching the upcoming low-radius curves.

The final model yields consistency indicators that depend on the road geometry and on each driver's behaviour, which can be used to estimate the safety of contiguous elements of a road segment, as well as a global indicator of geometric design consistency.

2. DATA COLLECTION AND METHODOLOGY

A set of two two-lane rural highway segments in Portugal were selected to collect the data. The segments of road are characterized by a low traffic volume with an annual average daily traffic (AADT) of around 6,500 vehicles. Some sections of the road are shown in *Figure 1*. Since the object of this study was focused on horizontal alignments, the sample data were limited to relatively flat stretches (grades lower than ±4%). A total set of 47 curves was analysed for each direction of traffic, and the radius of the circular curves varied between 40 m and 500 m. The pavement was in good condition throughout the extension of the road and the segments analysed were 3.6 km and 9.2 km long. All the road segments presented a width by an average of 7 metres and pavement shoulders throughout most of its extension, with an average of one metre width on each direction of traffic. The speed data were collected between August and September during workdays between 10:00 a.m. and 12:00 p.m., and between 3:00 p.m. and 5:00 p.m. under dry weather conditions. None of the selected road segments presented important intersections.

The drivers were randomly selected from a set of several drivers who volunteered to conduct the experiment, considering driving experience as the most decisive aspect. All drivers had more than five years of experience in an average of more than 15,000 km/year. No other criterion was considered, e.g. age, gender, etc. to minimize the variables involved at this stage of the research. Each driver was allowed a testing period before each field session.

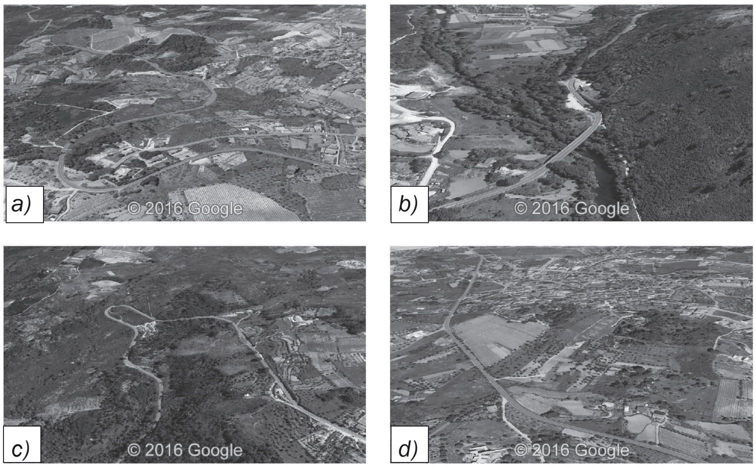

Figure 1 – Sections of the two-lane rural highway segments (adapted from Google Earth)

The equipment installed in the vehicle was a data logger from Race Technology Ltd (DL1 MK3 model) that has a built-in accelerometer with three axes and a 20 Hz GPS, enabling the collection of reference data related to the position on the road, speed, acceleration and the corresponding time stamp. The equipment was configured to record at 10 Hz.

All laps were recorded in real time with the support of the installed equipment and checked afterwards with the video footage to guarantee the quality of the results, i.e. to verify whether or not that particular driver had been influenced by another vehicle, therefore preventing free-flow conditions.

The data obtained from the equipment allowed the modelling of every road segment with the accuracy needed to obtain various geometric characteristics of the horizontal alignments. In other words, using the coordinates taken from the equipment, exported from the data review program (RT Analysis software), and using AutoCAD Civil 3D, it was possible to determine the beginning point and the end point of each element of the road segments (tangents, curves, transition curves) and consequently the geometric characteristics of each road segment. For this task the GPS antenna was placed on the left side of the car roof and the driver followed as close as possible to the road centreline.

The software provided by the data logger offers, in addition to the ability of exporting data to a spreadsheet, an extensive analysis of the journeys made by the drivers on the road segments, i.e. path view overlaid with satellite maps, speed and acceleration diagrams, synchronized video footage with the position on the road and the corresponding speed diagram, etc. Since the equipment takes into account GPS, it is assumed that some positioning errors might occur, but since the recordings are taken at intervals of 0.1 seconds those errors did not influence the modelling of the geometric characteristics of the road segments.

After data processing, there was the need to use only "curved and tangent sections" of the road to develop the overall model. For that matter, the extension of the transition curves was allocated between "curved and tangent sections", taking into account the following rules: a) the "tangent section" comprises the tangent length and 1/3 of the length of each contiguous transition curve; b) the "curved section" includes the length of the circular curve and 2/3 of the length of each adjacent transition curve. This option reflects the shape of the most used transition curves (clothoids) that are practically straight lines in their initial part. The curvature diagrams presented in this paper also reflect these rules.

3. DEVELOPMENT

3.1 Operating speed model on curves

From all the variables of the horizontal alignment on both segments of the road, the most important are the curve radius, curve length and deflection angle. The curve radius varied from 40 m to 500 m, the curve length from 33 m to 232 m, and the deflection angle from 9.85° to 120.75°. The relations between these variables were studied with the purpose of developing several regression models. The curve radius was the variable that revealed the highest correlation to the operating speed, and the curve length revealed the least correlation. Therefore, the curve radius was used as the explanatory variable to develop various models.

The operating speed data used to develop the model correspond to the minimum value observed in each of the 47 curves for each driver. A total of 284 observations were obtained and validated.

The assumption that the operating speed on curves is constant was not observed. From the analysis of the continuous speed profiles, most of the deceleration and acceleration occur within the curve. Only in very specific situations a constant speed was observed, for instance, curves that are very close to each other and have a small tangent between them, or curves with similar radii. These situations tend to prevent the driver to increase or decrease the travel speed, which leads to the decision, on most occasions, to maintain a constant speed between these elements.

From a regression analysis resulted the exponential model shown in *Figure 2* with the radius as explanatory variable and R^2=0.511, and it can be obtained by the following equation:

$$V_{85} = V_0 e^{\left(\frac{-3.86}{\sqrt{R}}\right)} \quad (1)$$

where V_{85} is the operating speed on curve (km/h), R is the radius (40≤R≤500 m) and V_0 is the top speed, that can vary according to the road type; in this case, V_0=81.3 km/h.

The model shows a high slope for small radii and decreases as the radius gets bigger and speeds tend towards the posted speed limit (70 km/h on most segments). It indicates that for the curves with large radius this variable is not as significant in the choice of speed as for curves with small radius. This analysis is consistent with the model developed by Pérez-Zuriaga et al. [20].

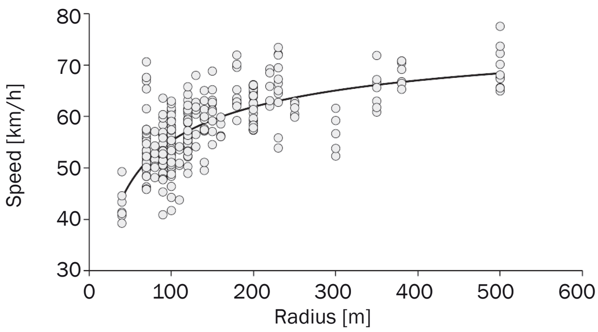

Figure 2 – Operating speed model on curves

3.2 Operating speed profile model

This section presents the development of the operating speed profile model, along a road segment, that is primarily based on the car-following model by Gipps (1981) [21]. The car-following models attempt to replicate the behaviour of drivers when they follow other vehicles through complex algorithms. They are typically used in microscopic simulation models and aim to generate the response of a driver relative to the vehicle ahead. The Gipps' model, associated with the microscopic simulation application Aimsun, is currently one of the most popular safe distance models. These models assume that drivers tend to keep a safe distance to vehicles that they follow. The distance is calculated as the distance that avoids collision in case of a sudden deceleration.

For this application, the Gipps' model is adapted according to a set of rules in order to translate the observed behaviour of isolated drivers when approaching and leaving a circular curve (see *Figure 3*). The main changes are:

- A fictitious and static vehicle is placed at the beginning of each curve, and assigned the minimum curve speed given by *Equation 1*. This activates the model's deceleration mode and forces the speed transition from the straight segment to the curve;
- The parameter that represents the spacing between vehicles at rest (physical length of the leader vehicle added to the minimum desired spacing) is allowed to take negative values. This results in vehicles completing the deceleration after the beginning of the curve;
- Vehicles are allowed to begin the acceleration to the desired speed before the end of the circular curve.

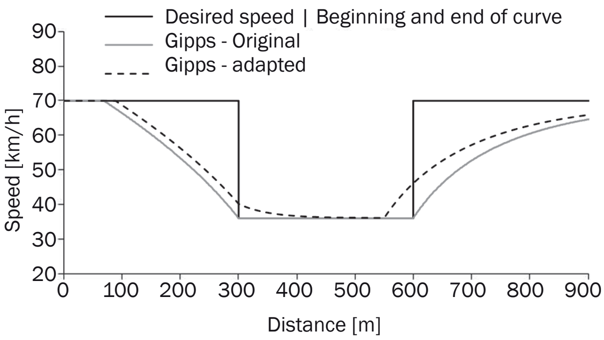

Figure 3 – Adaptation of the Gipps' model

For each time step, the vehicle speed is calculated in the function of the following parameters: desired speed, vehicle position, vehicle speed, space headway, and speed of the fictitious leading vehicle. These calculations require quantifying a set of geometric variables and behavioural parameters. The road geometry is described as a list of distances to the origin, corresponding to the start and end of each curve. The desired speed on each curve is calculated as a function of its radius. The behavioural parameters must be calibrated from field data and are specific to a given driver.

Calibration

Not all parameters from the original Gipps' model are involved in the optimization. For example, a constant value of 0.1 s was assigned to the time step/reaction time, since this parameter is only relevant to describe real car-following scenarios. The calibration problem was formulated as follows:

$$\begin{aligned} &\min_{v,a,d,S} f\left(\mathbf{M^{obs}}, \mathbf{M^{sim}}\right) \\ &\text{s.a.} \quad 11.1 < v < 25.0\,\text{m/s} \\ &\qquad\;\; 0.3 < a < 2.0\,\text{m/s}^2 \\ &\qquad\;\; 0.3 < d < 2.0\,\text{m/s}^2 \\ &\qquad\;\; -5 < S < -50\,\text{m} \end{aligned} \tag{2}$$

where f is the goodness of fit function that measures the distance between the observed and simulated measurements $\mathbf{M^{obs}}$ and $\mathbf{M^{sim}}$; v is the desired speed on the straight elements a is the maximum desired acceleration d is the maximum desired deceleration; and S is the spacing between vehicles at rest.

The fitness value f is defined as the root mean squared error (RMSE) corresponding to the difference between the simulated and observed speed profiles for a given driver, determined as follows:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} \left(V_{M,i} - v_{S,i} \right)^2}{n}} \tag{3}$$

where v_M and v_S are the measured and simulated speeds, respectively, in the generic spatial segment i; and n is the number of segments.

Among the set of optimization techniques, Evolutionary Algorithms (EAs) have recently received increased attention. Genetic Algorithms (GAs) are often used to represent EAs, and they have been used in various complex simulation and optimization transportation-related problems due to their powerful search and optimization capabilities. These adaptive meta-heuristic search techniques are based on the mechanism of natural selection and natural genetics that potentially guarantees a robust search, and near-optimal solutions [22].

The optimization framework was implemented in Matlab using the built-in genetic algorithm tool. The algorithm starts by generating an initial population. For each set of parameters, the speed profile for the entire length is calculated and compared with the measured speeds to compute the fitness values. When all individuals are evaluated, the GA generates a new population: besides elite children, who correspond to the individuals in the current generation with the best fitness values, the algorithm creates crossover children by selecting vector entries from a pair of individuals, and mutation children, by applying random changes to a single individual (MathWorks 2004, Vasconcelos et al. 2014) [23, 24].

After approximately 50 generations (for each driver), the GA achieved a convergence condition and returned the optimal solutions for all the parameters (see *Table 1*).

The maximum RMSE of 1.503 m/s observed for driver C resulted from the optimization process. The operating speed profiles resulting from the observations and simulations (optimal values) are displayed in *Figure 4*. Only a small stretch of one segment of the road is presented for better viewing purpose, but the associated RMSE corresponds to the analysis of the whole segment of road.

Application and validation

From the same set of optimum parameters previously determined by the optimization process, and in order to validate the model, the behaviour of the drivers was simulated but this time in the opposite direction of the road. The speed profiles were also generated using a Matlab script but without the use of the optimization algorithm. The resulting speed profiles are shown in *Figure 5*.

The RMSE that results from the first simulation (driver A) is equal to 1.259 m/s, which compared to the value observed in the calibration phase is superior in only 0.222 m/s, revealing a very satisfactory adjustment to the observed driver's behaviour.

Regarding the second simulation (driver B), it is noticed that the model fits in a satisfactory manner into the behaviour of the driver, resulting in an RMSE of 1.695 m/s, with only a difference of 0.357 m/s relative to the calibration phase.

In the third simulation (driver C), the associated RMSE is equal to 1.558 m/s, and when compared to the value verified in the calibration phase it is superior in only 0.055 m/s, i.e. almost null, which indicates that the parameters obtained in the calibration process are robust.

In short, the use of this model after calibration, and for a particular driver, makes it possible to reproduce the behaviour of that specific driver in similar situations and with high accuracy. Therefore, this procedure is translated into a model that may be applied to two-lane rural roads, and can be used as a surrogate method to estimate the operating speed profiles for various drivers individually.

Table 1 – Optimal parameters obtained for the drivers

Set of parameters	v [m/s]	a [m/s^2]	d [m/s^2]	S [m]	$RMSE$ [m/s]
Driver A	19.47	1.96	0.86	−19.40	1.037
Driver B	23.03	1.22	1.25	−6.22	1.368
Driver C	20.88	1.92	1.50	−37.57	1.503

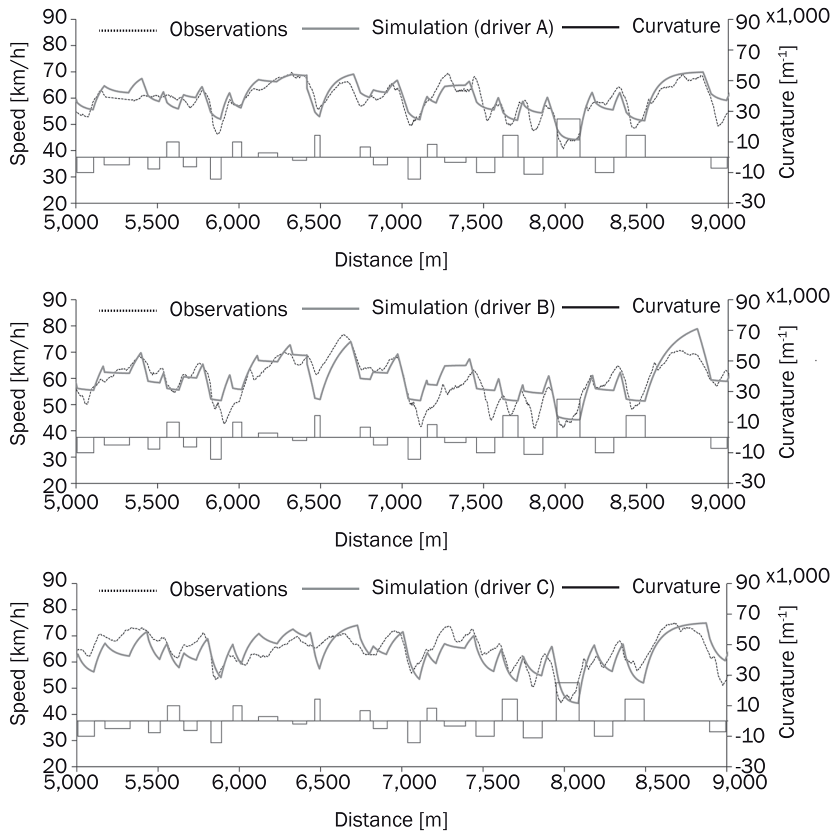

Figure 4 – Operating speed profiles per driver resulting from the calibration procedure

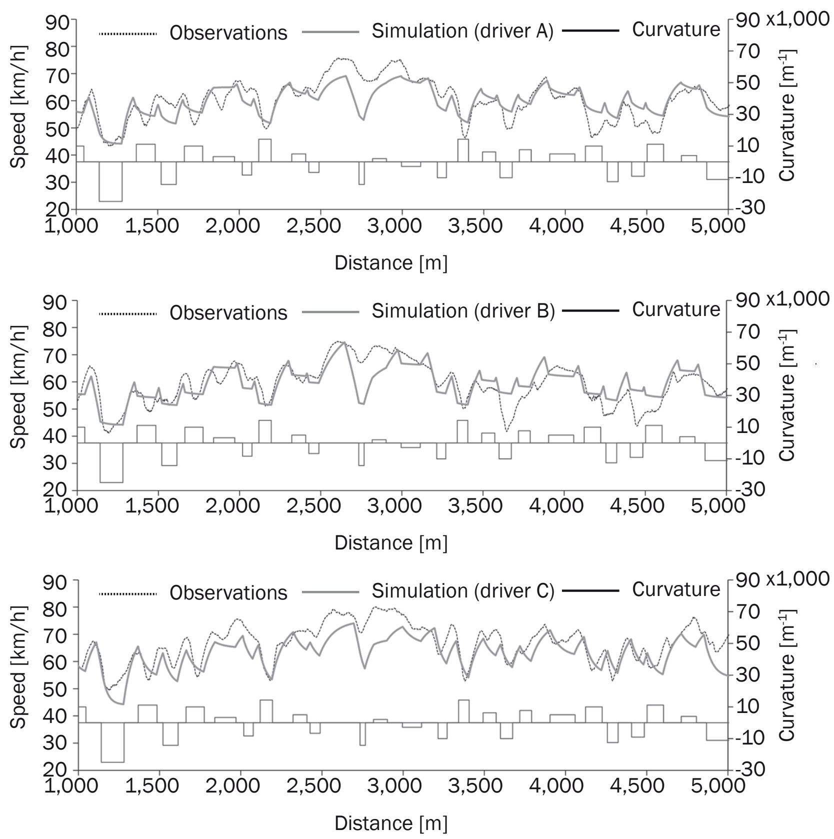

Figure 5 – Operating speed profiles per driver resulting from the validation procedure

3.3 Design consistency indicator

One of the objectives of this study was to develop a design consistency parameter using the model developed beforehand to predict the operating speed profiles based on the driver's behaviour. Therefore, from the various factors analysed in the optimization process, speed reduction is the one that can relate to safety when approaching a curved element of the road.

Since the operating speed profile model assumes that the deceleration rate is constant along the path, the immediate consequence of the transition from fast elements (tangents) to slow elements (curves), is that in situations when more unbalanced speeds occur, the deceleration distance is greater. Then, the deceleration distance that occurs in tangent-to-curve transitions can be considered as a good indicator of design consistency.

For that matter, in case of a consistent road, it is supposed that most of its length is travelled at a desired speed, resulting in lower deceleration distances. An indicator to measure the deceleration distance is proposed, denoted by L_d, and an analysis of this indicator is present in *Figure 6*. It represents a simulation for a segment of the same road and using the same optimal parameters of the same three drivers. Each diagram shows the operating speed and the deceleration distance. Each horizontal bar indicates the beginning and the section of each deceleration segment.

The difference in drivers' behaviour is clearly noted when comparing all the operating speed profiles. However, when observing the design consistency parameter L_d (deceleration distance) for the first two drivers, the difference is not very significant, revealing a consistent indicator for this particular segment of road that was analysed. When looking at the third driver (lowest diagram), the difference to other drivers is a bit more significant. This happens due to the more aggressive behaviour of that particular driver, which begins decelerating too late, in most parts, already inside the curved element. Nevertheless, when comparing the critical sections of the indicator with the other drivers it remains consistent, although with less intensity.

From a global analysis, there are four zones (each zone corresponds to 300 m of distance, i.e. zone one corresponds to the section that begins at 3.0 km and ends at 3.3 km) that need to be checked regarding design consistency: zones one, four, six and ten of the diagrams. These zones are constant to all drivers.

It is also possible to define a global indicator of design consistency for the entire road segment. This indicator would be the sum of all the deceleration distances divided by the total distance of the road segment. This would result in an indicator per driver, and the global indicator would be the mean of those individual indices. However, there is the need to associate that global value to design consistency thresholds, and for that matter further studies need to be conducted.

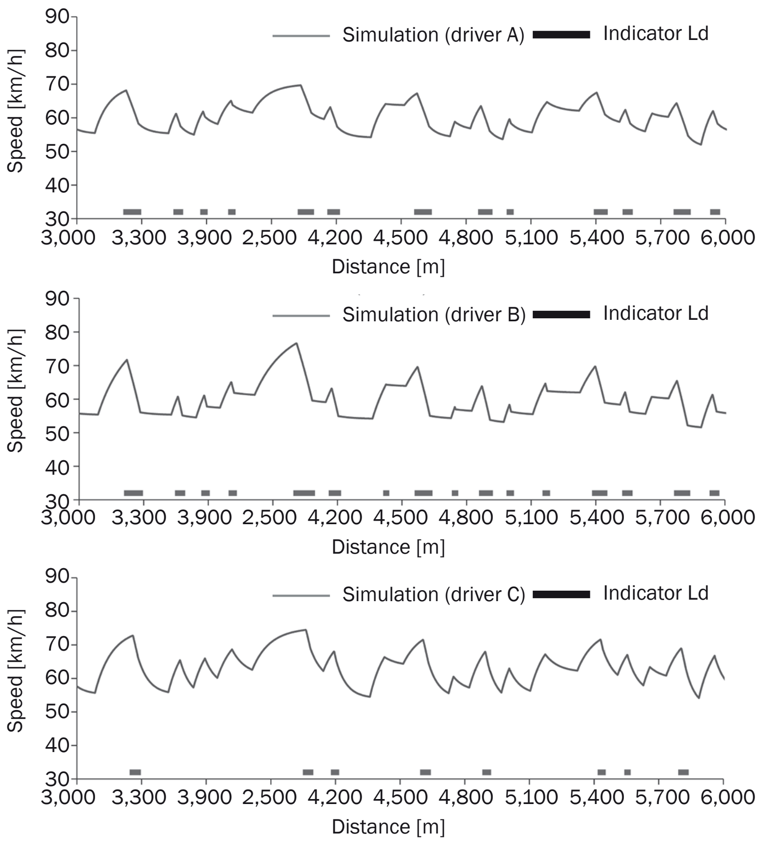

Figure 6 – Design consistency parameter analysis

4. CONCLUSION

The concept of design consistency was defined as a way to prevent unexpected changes to geometrical characteristics of contiguous road elements and combinations of elements that do not comply with drivers' expectations. Some of the methods that exist today to evaluate the design consistency on two-lane rural highways are based on the estimate of operating speed profiles that do not replicate the actual driver behaviour. The verification and evaluation of the operating speed on particular elements of the road can become, in most cases, excessively restrictive and inappropriate to ensure proper comfort and safety to all drivers. For that matter, it is essential to have models that are able to predict the operating speed regarding the prevailing characteristics of the road and the behaviour of the drivers.

It was established that our model, based on Gipps' car-following equations, replicates satisfactorily the behaviour of several drivers. The design consistency indicator presented in this paper is an innovative tool that can be used as a surrogate measure to estimate the safety of contiguous elements of a road segment within the parameters of the simulation, which takes in consideration the driver's deceleration when approaching a circular curve. It can also be used as a global indicator of geometric design consistency for two-lane rural highways when the analysis is made for several drivers.

Although the results turned out to be satisfactory, it will be necessary to validate the model for other roads that have different geometrical characteristics, and to perform the calibration to a large number of drivers.

While the indicator for design consistency explains the influence of the deceleration distance, it was found that the results were conditioned by a few behavioural parameters. This means that, in order to generalize the conclusions to a national or regional population, it would be necessary to expand the drivers' sample in order to include different behaviour classes, as the critical sections of the road may vary for each class.

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AVALIAÇÃO DA CONSISTÊNCIA DO TRAÇADO DE ESTRADAS INTERURBANAS COM BASE EM PERFIS DE VELOCIDADE CONTÍNUOS

RESUMO

Verifica-se que os acidentes rodoviários tendem a ser mais frequentes em locais onde uma mudança abrupta nas características da estrada viola as expectativas naturais do condutor. A maioria dos métodos utilizados para avaliar a homogeneidade do traçado é baseada em perfis de velocidades simplistas que fornecem uma descrição rudimentar da dinâmica do veículo ao longo da estrada. Este artigo apresenta uma nova abordagem para avaliar a homogeneidade do traçado, com base em perfis de velocidades contínuos. Esses perfis baseiam-se no modelo de car-following de Gipps, adaptado para simular o comportamento do condutor na aproximação de curvas horizontais em regime livre de circulação. A metodologia usada para calibrar e validar os parâmetros comportamentais do modelo de Gipps a partir de dados de campo é apresentada e aplicada para avaliar os perfis de velocidades de três condutores em vários segmentos de uma estrada interurbana. A calibração tem por base as características geométricas obtidas com recurso a um veículo instrumentado e segue um procedimento automatizado que visa minimizar as diferenças entre os perfis de velocidades simulados e observados. O indicador de homogeneidade é baseado nas distâncias de desaceleração, permitindo ultrapassar algumas das limitações dos métodos existentes.

PALAVRAS-CHAVE

consistência de traçado; perfis de velocidade; segurança rodoviária; velocidade operacional; aceleração; desaceleração; Gipps;

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