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Derive a mathematical model to predict instantaneous vehicle speed for different road conditions

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ABSTRACT

Speed can be described as one of the most important factors that road users consider to evaluate the convenience and efficiency of a certain route. In addition, along with other factors such as travel time and cost, speed may affect the decisions made by drivers in selecting between different route alternatives. Speed has also been recognized as one of the measures that designers can use to examine road consistency and driver expectancy on roadways.

In design guides, highway elements are designed by selecting a design speed that is consistent with the anticipated operating speed. In general, the design speed is selected with respect to road class, topography, and land use. Several factors influence operating speeds. There is a large body of published literature that presents operating speed as a function of road parameters such as horizontal curve radius, vertical grade, rate of vertical curvature, traffic flow characteristics, and cross sectional dimensions.

This report derive a mathematical model to predict instantaneous vehicle speed for different road conditions which accurately describes the instantaneous speed profile of vehicle moving on the road. A mathematical model is able to predict vehicle speed time history or distance time history. Input is taken as GPS data (coordinates etc.), IRI road roughness and road parameters as stated above.

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I. INTRODUCTION

An inconsistency in design can be defined as "a geometric feature or combination of adjacent features that have such unexpectedly high driver workload that motorists may be surprised and therefore drive in an unsafe manner" (*1*). On the contrary, design consistency has been defined in the literature as the degree to which a road is designed to avoid critical driving errors that can lead to collision risk (*2*). In other words, design consistency implies that the geometry of a road
does not violate the expectations of the motorist to drive and control the vehicle in a safe manner(*3, 4*). Design consistency has been often related to speed, e.g. a sudden change in the characteristic of the roadway can surprise motorists and lead to speed errors (*5*). Therefore, a consistent alignment would ensure that most drivers would be able to operate safely at their desired speed along the entire alignment.

Using design consistency as surrogate measure of safety, its correlation with crash frequency has been widely demonstrated by several studies carried out in different countries (e.g. *6, 7, 8, 9, 10 ,11, 12, 13*).On the basis of this approach, the 85th percentile of free-flow speed distribution is commonly used to represent "operating speed" for design consistency evaluations. Predicted operating speeds are compared to each other or to the designated design speed to evaluate design consistency and crash risk. It is therefore of primary interest to develop methodologies suitable for estimating the speed behaviour of drivers. The traditional approach to evaluating design consistency (*14*) is based on calculating the operating speed of the drivers separately on the curved and the tangent sections. Speed on curves is used to evaluate the consistency with design speed and available side friction. Speed differential between curve and tangent is used to evaluate the consistency in the transition between two successive geometric elements. Based on these assumptions, many models for estimating the operating speed exist in the scientific literature.

An extensive and complete review of the state of art on speed models is not the goal of this paper. The reader can find better references in broader and more complete publications (e.g. *15, 16, 17*). Rather, in the following part of the paragraph, relevant literature will be cited to highlight some critical points forming the basis of this paper, which focuses on a continuous speed profile model. Operating speed prediction models, especially in the past, have been limited above all to horizontal curves (*5, 18; 19*), at least considering in the same regression expression the tangents a "curve" with zero value of curvature. Relatively few models have been developed to estimate the speed on tangent sections. There are many reasons to justify this lack of modelling.

Speed on curve is considered the principal input for safety evaluations; moreover, goodness of fit of speed models on curves is easier than the prediction of speed on tangent sections because of the strong correlation of speed on curve with a well-known and limited number of variables (i.e. curvature, super elevation). On tangent sections the vehicle speed depends on a wide array of road features, such as length of the tangent section, radius of the curves before and after the section, vertical alignment, cross-section width and available sight distance. Krammes et al. (20) conducted one of the most comprehensive studies on horizontal alignment to develop a speed profile model to check design consistency. The recommended multiple-regression equation to predict the 85th percentile speed is one in which all the variables are related to the geometry of the curve. Another suggested equation includes the speed on the preceding tangent as a measure of the desired speed. However, the desired speed was difficult to predict, and in the study this version of the model was not recommended by the authors. The analyses of 162 tangent sections on two-lane rural highways (21) showed that when determining 85th percentile speed in the middle of a tangent section, it is necessary to observe a longer section that includes the preceding and succeeding curves, since these constitute the primary variables affecting speed.

Moreover, even if using only two data points to determine speed differentials is valid, the midpoint of tangent and midpoint of curve might not be the appropriate locations. As suggested by McFadden and Elefteriadou (22), "Research that identifies where drivers reach the maximum speed on the approach tangent and minimum speed on the horizontal curve would be valuable." From this point of view, another concern has to be considered. Many studies are based on spot speed data collected from stations on the side of the road. This kind of speed measurement can induce bias or human errors:- the location of the measurement sections (e.g. middle tangent, middle curve) is pre-defined by the experimenter and it provides discrete information on the actual speeds; - the accuracy of the speed observations could be reduced arising from the cosine error induced by the deviation between the reading beam of the Radar/Lidar gun and the actual driving direction; - the probability of having drivers changing their natural driving tendency upon perceiving the test equipment as speed enforcement weakens the reliability of data collection; Only a continuous speed profile provides a comprehensive representation of the operating speed at each point of the alignment. A speed profile is essentially a plot of operating speeds on the vertical axis versus distance along the roadway on the horizontal axis.

With respect to the overall state of the art, few speed models allows exploration of speed highway geometry relationships at all points along the speed profile.Fitzpatrick, et al. (23) developed an operating speed prediction methodology for inclusion in theInteractive Highway Safety Design Model (IHSDM). Similar to previous methods, operatingspeeds were estimated for horizontal curves based on the radius of curve. Vertical curvature wasalso considered in the development of speed prediction models.

Among the final recommendations of this study, the following are of interest for the present paper:- Additional insight into the influences of speeds on tangent sections of various lengths andgrades is needed.- The acceleration and deceleration models developed here were related exclusively to the impactof the horizontal curve. It is recommended that a similar effort be undertaken to assess theimpact of vertical curves, as well as of horizontal-vertical combinations, on acceleration anddeceleration profiles.

Ottensen and Krammes (24) developed a speed profile model. For curves, a model that is linear with respect to degree of curvature was selected as the most appropriate. As it was not possible to develop a statistical model for long tangents, a constant value of 97.7 km/h was considered reasonable estimate of the 85th percentile speed on tangents. The acceleration and deceleration rate of 0.85 m/s2 that was estimated by Lamm et al. (25) was adopted without validation, and it was recommended that this assumption be validated.

Nie and Hassan (26) stated that current speed profiles are constructed based on assumptions that might not be realistic. One of these is that acceleration and deceleration occur only on tangents(i.e., that speed is constant throughout a curve), which is generally not the case. Moreover, they concluded that "there is no specific measure available to date to quantify the speed increase when departing a horizontal curve".

Figuera and Tarko (27) divided the road section, from the speed point of view, into four segment types: tangents, deceleration segments, effective curves, and acceleration segments. Separate models were developed for each type of segment. The models developed for the deceleration and acceleration segments made it possible to determine the spots where an average driver starts and ends changing speed.Perez et al. (28) used a continuous speed profile to determine the beginning and the end points of deceleration and the associated 85th percentile of deceleration rate using radius as explanatory variable.In both the previous studies,

the assumption of a constant acceleration/deceleration rate results in a linear speed profile that represents an approximation of actual driving behaviour as reported inthis and other studies (*29*) based on continuous tracking of driver speed and acceleration alongthe route.
According to the state of the art, the following limitations and deficiencies of the existing profilespeed models can be identified:
1. Operating speed prediction models generally focus on tangent-curve combinations that meetcertain site selection criteria without a comprehensive consideration of the entire alignment andsurrounding roadway environment, such as adjacent horizontal or vertical design elements;
2. Relatively few models consider combinations of horizontal and vertical alignment and variablesrelated to tangents;
3. Relatively few models include acceleration/deceleration models for speeds approaching andexiting curves. A majority of models estimate a constant speed at curves and tangents withconstant acceleration/deceleration rates for transition;
4.speed surveys based on measurements taken from stations at the side of roadway can inducebias or human errors. Considering the above statements, despite the relevant state of the art, the necessity of newstudies exploring a different approach to research on driver speed behaviour is evident. In thisregard, the main objective of the research presented in this paper is to analyse driver speedbehaviour with continuity along the road alignment using actual driving data collected directly onboard the vehicle. Specifically, the authors attempt in this paper to model a continuous speedprofile on two-lane rural roads.

II. EXPERIMENT

From the experimental point of view, the strength of the methodology is that speed data arecollected with continuity along the vehicle path and not with spot measures using radar devices or other sensors located in fixed points. To attain this target, during the experiment the positions of several vehicles were monitored using GPS technology. The survey was carried out using a GPS receiver (double-frequency, GPS & GLONASS) placed on board the vehicle supported by a fixed master station in order to perform a post-differential correction to achieve high accuracy (centimeters) of the spatial coordinates recorded with a sampling frequency of 1 Hz. The experimental tests were carried during day, good weather and free flow conditions. The drivers traveled along several roads in both directions.

Free-flow speed is considered to be the speed at which the driver operates a vehicle when unconstrained by other drivers. Free-flow speeds are typically defined as having time headways of at least five or six seconds (*17, 30*). During the driving test, with the help of a chronographand a form, filled in during the test by an assistant seated in the rear seat of the car, it was possible to record the sections in which the drivers were conditioned by other vehicles (less than 5 seconds of headway). Moreover, all the times in which the driver changed his/her driving behavior due to external factors not dependent on the road geometry (e.g. major intersections, road works, etc.) were marked as artifacts, in order to discard them during data processing. The drivers' trajectories are not coincident and not parallel to the road axis since each driver subjectively interpreted the path. In order to compare the collected data, it was necessary to define a standard axial reference along the road alignment. Given the large amount of data to be processed, software was developed to project each sampled point on the reference road axis.This made it possible to transform the spatial coordinates (x,y,z) for each vehicle position from the GPS survey to curvilinear abscissa along the road axis. This process also allows the vehicleposition to be related to the horizontal and vertical geometric characteristics of the road stretch.Using the GPS technique for each point sampled it was possible to know not only its position inspace but also in time. Thus it was possible to calculate the speed of each participant in the test, taking into account the space-time difference between two points (Figure 1).

Point	Latitude (deg)	Longitude (deg)	Altitude (m)	Bearing (deg)	Speed (m/s)
1	18.531	73.849	475.042	160	3.0501
2	18.531	73.849	468.699	0	2.3919
3	18.531	73.849	468.74	0	3.052
4	18.531	73.84	468.88	197	2.7571
5	18.531	73.84	468.992	200	2.7571

Table 1.GPS data collection

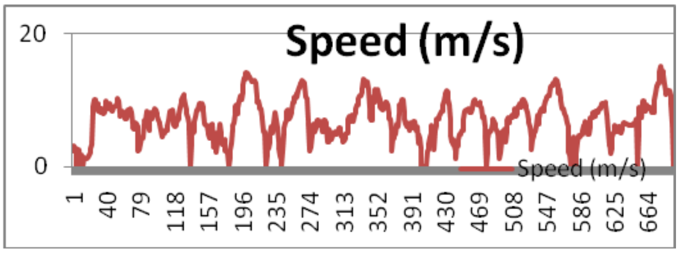

Fig 1.Speed Vs distance

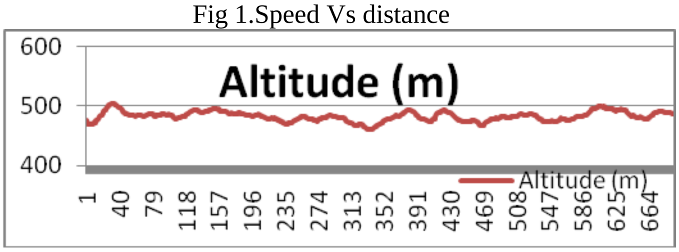

Fig 2.Altitude Vs. distance

Bearing angle

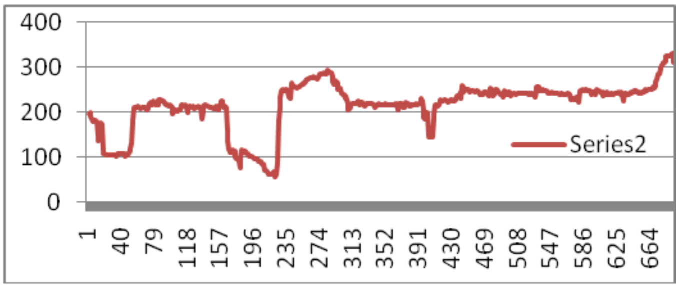

Fig 3.Bearing angle vs. Distance

Speed	
standard deviation	3.066063754
mean	7.027
kurt	-0.201955191
min	0
max	15.0853
Altitude	
standard deviation	8.115200743
mean	482.1449625
kurt	-0.072465529
min	460.329834
max	503.4203186
bearing angle	
standard deviation	54.05471242
mean	215.8802309
kurt	1.052103139
min	57
max	331

Table 2.stastatics of data collection

III.SPEED MODELING

As the first step of the analysis, the correlation between speed (V) and horizontal curvature (1/R) was analyzed, with R equal to curvature radius of the road axis. The best fit was identified using an exponential regression (Figure 2). The regression equation is given in the form:

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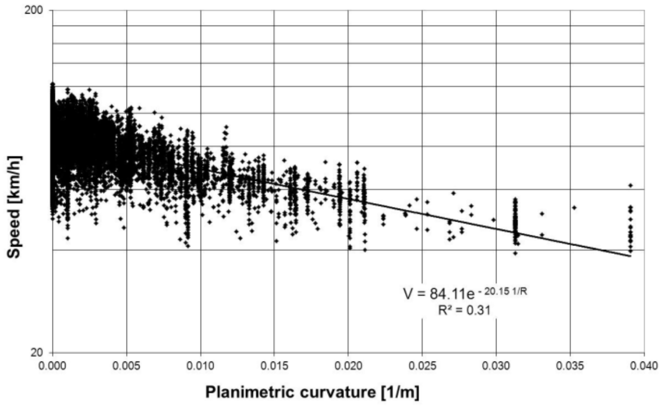
V = 84.11 · e-20.15·1/R (1) With R: curvature radius [m]

It must be pointed out, that in equation (1) V is an estimation of the average speed of the sample.



The relatively low value of R2=0.31, shows that curvature alone in not a good estimator of operating speed. To take into account the geometric context of the road link in which an element is inserted and its correlation with the driving speed, a new geometric parameter more comprehensive than spotcurvature must be defined. First of all, it must be stated that driver behavior is not influenced only by the spot geometry of

the section of the road where the user is traveling (e.g. local curvature). Drivers perceive the geometric features related to the position of the vehicle according to dynamic sensations

(accelerations) and vehicle sensors. Driver vision, depending on speed, is usually focalized on sections 20-100 meters in front of the vehicle. Moreover, the driver has a "memory effect" of the road already traveled.

Therefore, road user behavior is determined not only by the features of the road section he/she is traveling but also by the expectations and the immediate holistic perception of the road. Expectation is based on the memory of the road he has just traveled and perception of the visualinformation he gets at the present moment. Normally, when we enter an unknown new road we might have some expectations about what is out there. If the road is a national main road we expect a relatively high road standard, and if it is a local road we might expect a road with narrow geometric standards. But after just a few kilometers we have already built up some expectations on how the road will continue further on. The best and most common expectation is that the road will continue to look as it did in the preceding part

IV.CONCLUSIONS

The paper presents a modeling of driver behavior in terms of speeds for two-lane rural roads. The model was obtained through GPS sampling of the positions of several test drivers who travelled a number of different roads in both directions.

It was proposed to develop a regression model based on two new geometric parameters: averaged horizontal curvature and averaged vertical grade. The model form allows the estimation

of a continuous speed profile depending not only on the spot geometry of the section of the road in which the user is traveling but also on the horizontal and vertical alignment of the road already travelled and to be travelled.

Thus, it was possible to obtain a speed value closest to the real one; and the model is also able to correctly estimate different speeds for two curves with equal radius but having different

preceding and following alignments.

At the same time, starting from the evaluation of the mean speed, any desired percentile of the operating speed can be carried out from the estimation of the standard deviation of speeds. A significant correlation was found between curvature and standard deviation of speeds, showing how an increase in the curvature reduces both the mean speed and the speed dispersion.

From a practical point of view, even though the computation of new geometric variables such as the weighted average of the preceding and following alignment is more complex than the local curvature or grade values, they can be easily carried out using simple excel sheets. Moreover, due its ability to define a continuous speed profile, it is simple to implement the model in a computer program, such as IHSDM, to perform design consistency checks.

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