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OPERATING SPEED MODELING IN TWO-LANE HIGHWAYS

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DOCTORAL THESIS IN TRANSPORT SYSTEMS

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POPH
PROGRAMA OPERACIONAL POTENCIAL HUMANO

To my mother and my wife

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ABSTRACT

Operating speed is one of the most important factors in road design, evaluation and monitoring. For road designers, the operating speed has been gaining relevance over the last few decades, with several official guidelines urging to anticipate the operating speed estimation in the design process, with the aim of reflecting driver expectancy in the selection of design speed. Therefore, the operating speed is currently regarded as a means to improve design consistency and safety performance when setting road geometrics. Likewise, operating speed is a crucial performance measure during the lifespan of a roadway infrastructure. Drivers' evaluation of travel time, cost, and convenience determine their route choice and are strongly influenced by their perceptions of the operating speeds of different routes. In turn, road managers use the operating speed as an input for multiple actions oriented to alleviate congestion, promote safety, and improve the environmental efficiency of the road system.

To address the problem of estimating road operating speeds, the research community, public authorities, and road operators have conducted increasing efforts to deliver adequate speed predictions tools and study its main drivers under different contexts. However, several authors point toward the need for further research aimed to fill the gaps in the literature. The deficiencies identified in the existing speed models are mainly related to the attention placed on certain geometric elements to the detriment of others, the preclusion of relevant variables, the limitations of traditional model formulations, and the debatable assumptions of driving behavior.

This thesis aims to enhance operating speed prediction capabilities in two-lane rural highways by delivering five new models with distinctive formulation and increased applicability. The work starts with two exploratory studies, one regarding the definition of free-flow traveling conditions in Portugal, and another, conducted in simulated environment, aimed to clarify the interaction between the cross-section characteristics and the operating speed. The findings from these studies are used in the subsequent speed model development. Models are estimated through regression techniques applied for the first time to operating speed modeling, using a database consisting of geometric and roadside interference parameters of seven Portuguese two-lane highways and the speeds of more than 23,500 observed vehicles.

The set of developed models is composed of four spot speed prediction models, applicable to individual curves and tangents of the horizontal alignment, and one segment speed prediction model, applicable to a length of roadway. The first model consists of an 85^{th}-percentile speed prediction model, estimating the effects on spot speeds of on-site, upstream and downstream effects through an exponential regression. This model, calibrated for two-lane highways classified as National Roads in Portugal, serves as the starting point to develop improved methods to estimate percentile speeds. In this sense, this research proposes the operating speed frontier model (OSFM) formulation, representing a completely new approach to speed modeling, based on the principles of stochastic frontier production modeling used in econometric analysis. This formulation allows for the estimation of any percentile speed from a deterministic frontier representing the maximum operating speed as an exponential function of road characteristics. The OSFM formulation is introduced by the second operating speed model presented in this thesis, also calibrated for Portuguese National Roads. The third model improves the previous model specification by considering additional variables, and the fourth model enlarges the scope of applicability to roads of higher functional classification, i.e., Principal and Complementary Itineraries. Finally, an OSFM for road segments is developed, considering both road and traffic characteristics. The model, calibrated for Portuguese National Roads, is the only model to date applicable to segments of two-lane highways that was developed outside the scope of design guides.

The outcomes of this research address major gaps identified in the literature about operating speed modeling and significantly improve speed prediction capabilities. The ability to provide estimations of any user-specified percentile speed for horizontal curves, tangents, and segments of two-lane rural highways gives the models increased flexibility to assist practitioners in diverse applications related to road design and operations. This thesis provides a compilation of six scientific papers, one submitted and five published in peer-reviewed journals, corresponding to the main methodological steps of this research.

KEYWORDS: two-lane rural highways, road geometrics, free-flow conditions, operating speed, speed modeling, stochastic frontier models.

RESUMO

A velocidade operacional constitui um dos fatores mais relevantes no planeamento e operação de infraestruturas rodoviárias. Nas últimas décadas, este indicador tem sido mais intensamente utilizado por projetistas, acompanhando a evolução normativa de vários países no sentido da velocidade operacional esperada poder refletir as expetativas dos condutores no processo de seleção da velocidade de projeto. Assim, a velocidade operacional é vista como um instrumento de promoção da consistência do traçado e das condições de segurança, que pode, desde logo, ser utilizado no dimensionamento geométrico. A velocidade operacional é também crucial para a análise de desempenho e monitorização da infraestrutura em fase de operação. Por sua vez, os condutores habitualmente avaliam o tempo, custo e conveniência de um determinado itinerário através da sua perceção das velocidades operacionais ao longo desse percurso e dos alternativos. As entidades gestoras utilizam a velocidade operacional como parâmetro de análise em procedimentos diversos, como sejam a redução do congestionamento ou a promoção da segurança e eficiência ambiental do sistema rodoviário.

A comunidade científica, autoridades e entidades gestoras rodoviárias têm-se recorrentemente debruçado no problema da estimação da velocidade operacional, procurando averiguar os fatores que a determinam, bem como disponibilizar modelos de previsão adequados. No entanto, diversos autores apontam a necessidade de colmatar as limitações dos modelos existentes, que se prendem, sobretudo, com o maior foco dado a determinados elementos geométricos em detrimento de outros, a omissão de variáveis potencialmente relevantes, os constrangimentos associados às formulações matemáticas convencionais e a assunção de pressupostos questionáveis sobre o comportamento dos condutores.

Esta tese tem como objetivo principal o desenvolvimento de modelos de previsão da velocidade operacional em estradas rurais de duas vias, apresentando cinco novos modelos com formulação inovadora e aplicabilidade alargada. A investigação começa com dois estudos exploratórios, um deles dedicado ao estabelecimento do regime livre de circulação no contexto das estradas portuguesas, e outro, efetuado em simulador de condução, com o objetivo de clarificar as interações entre as caraterísticas do perfil transversal e a velocidade operacional. As conclusões destes estudos servem de suporte ao posterior desenvolvimento de modelos de previsão da velocidade operacional. Os modelos são estimados através de técnicas

de regressão numérica utilizadas pela primeira vez nesta área, sendo aplicadas a uma base de dados composta por variáveis caraterizadoras da geometria e do atrito lateral de sete estradas portuguesas de duas vias e pelas velocidades observadas de mais de 23.500 veículos.

Quatro dos modelos desenvolvidos aplicam-se a elementos geométricos da diretriz (curvas e retas) e um a troços de estrada. O primeiro estima o percentil 85 da distribuição das velocidades em elemento. É calibrado para Estradas Nacionais através de uma regressão exponencial, considerando as caraterísticas do elemento, do troço a montante e da visibilidade para jusante. Os pressupostos testados servem de base aos modelos de estimação de diferentes percentis da velocidade. Em seguida, propõe-se um modelo de fronteira da velocidade operacional (MFVO), calibrado para Estradas Nacionais, que introduz uma abordagem completamente inovadora à modelação de velocidades, baseada nos princípios e formulação dos modelos de fronteira estocástica de produção, oriundos da econometria. A formulação do MFVO permite a previsão de qualquer percentil da velocidade a partir de uma fronteira determinística de velocidades máximas de operação, estimada em função das caraterísticas da estrada. O terceiro modelo considera variáveis adicionais para melhorar a especificação do MFVO. O quarto alarga o âmbito de aplicação a Itinerários Principais e Complementares. Por fim, desenvolve-se um MFVO para troços de Estradas Nacionais, considerando a geometria, o atrito lateral e o tráfego. Excetuando algumas normas internacionais, não existe outro modelo de previsão da velocidade operacional em troços de estradas rurais de duas vias.

Os modelos resultantes desta investigação colmatam limitações nos atuais modelos de previsão da velocidade operacional, contribuindo significativamente para o estado da arte nesta matéria. A capacidade de estimar qualquer percentil de velocidades desejado em curvas, retas e troços de estradas rurais de duas vias confere aos modelos uma flexibilidade que os torna atrativos para aplicações diversas ao nível do projeto e da gestão rodoviária.

Esta tese apresenta uma compilação de cinco artigos publicados e um submetido a revistas internacionais com arbitragem científica, correspondendo aos seis principais passos da metodologia adotada.

PALAVRAS-CHAVE: estradas rurais de duas vias, geometria do traçado, regime livre de circulação, velocidade operacional, modelação de velocidades, modelos de fronteira estocástica.

CONTENTS

1

INTRODUCTION

1.1. BACKGROUND

Most of the road design guidelines adopted in different countries propose that the definition of the geometric parameters of a road segment is subject to the selection of a design speed, understood as the speed that is possible to adopt over the segment’s entire length. The design speed is selected according to the road’s functional classification, topography, and/or adjacent land use, using the methods proposed by the regulations. Additionally, many guides urge designers to maintain the same design speed over a significant length of roadway and contain specific tools to check the consistency of the selected geometric solutions. The objective is to avoid major variations of the road setting, and consequently, of speed, promoting a more homogenous and safer road environment. If a preliminary design is deemed unsafe during the consistency evaluation, the geometric characteristics are redefined through an iterative process that ends when a satisfactory design solution is achieved.

In the traditional approach, the methods to select design speed and control speed variations over a road segment are based on theoretical considerations related to vehicles’ dynamic equilibrium and/or ride comfort in curves. However, over the last few decades, the research community has been noticing that such principles may be insufficient to limit speed variations between successive design elements and reduce accident risk. Supporting this claim is the fact that some geometric variables, e.g., cross-section width, are inelastic with or not directly related to design speed, despite playing an important role in drivers' speed choice [1].

In this context, the concept of operating speed, reflecting the speed practiced by drivers at a given road element or segment, has gained relevance for road design. The underlying principle is that the minimization of speed variations can be more effective if real-world parameters and driver expectancy are involved in the design process. Conversely, the selection of a design speed in line with the expected operating speed should contribute to increase the safety and efficiency of the roadway system, as well as to conjugate the needs and interests of all road users.

Germany was the first country to adopt the concept of operating speed in design regulations, when, in 1973, introduced it as an evaluation parameter for design consistency [2]. Since then, other countries, such as Australia, Austria, Canada, France, Greece, Portugal, Spain, Switzerland, and the UK have followed in Germany's footsteps by incorporating to some extent the concept of operating speed into the design process [3–11]. Operating speed applications found in official design guides may include the selection of design speed, the setting of geometric parameters, the evaluation of design consistency, and the definition of speed limits.

In Portugal, where this research is developed, the operating speed definition proposed in the official design guide is termed "traffic speed", serving as a parameter to define certain attributes of the vertical alignment, namely the sight distances in roads with higher functional classification and the minimum radii of vertical curves [8]. However, the dimensioning of most geometric features and the evaluation of design consistency are subject to other speed concepts that do not derive from an experimental survey. Therefore, the intervention of operating speed in the road design process in Portugal is relatively small in comparison with the recent trends observed in other countries. It is foreseeable that this situation may change in the near future, as the proposal for the guidelines' revision [12] provides new operating speed models and uses speed predictions for design control purposes.

In addition to road design, the operating speed is one of the most important parameters used in the performance assessment during the lifespan of a roadway infrastructure. On the one hand, drivers choose their route by evaluating the convenience, travel time and cost associated with each alternative, aspects that are directly related to their perception about the operating speed. On the other hand, the operating speed is frequently used by road managers and concessionaires in safety and environmental evaluation, risk mitigation, and traffic management. The most common applications are focused on the implementation of traffic calming measures, the adjustment of speed limits, the control of emissions, the information about real-time traffic conditions, and the suggestion of alternative routes. Therefore, the credibility of these actions largely depends on the consideration of realistic values for the operating speed.

The most reliable manner to obtain information about the operating speed practiced at a given road is to perform *in situ* measurements [13]. However, as previously referred, an increasing number of road design guides are urging to anticipate the operating speed prediction in the design process. Additionally, even in existing roads, speed measurement equipment is not always available or easy to install due to regulatory or financial constraints.

To overcome such problems, the research community, public authorities, and road managers have developed numerous tools to estimate the operating speed. The academic approach usually adopts a microscopic perspective, with most of the studies proposing speed models for specific design elements of the road alignment, i.e., horizontal curves, tangents, vertical curves, and ramps, or for the combination of certain horizontal and vertical features. These models are commonly known as spot speed models. The study of the main speed drivers and the most accurate prediction tools, as well as the proposal of improved methods to evaluate design consistency and to predict and mitigate accident risk, are among the most common lines of research followed by academia. As previously mentioned, road managers and authorities have preferred to present methodologies to determine the operating speed and/or select the design speed over a road segment, i.e., over a substantial length of roadway, in order to establish directives for the design process and to ensure the adequacy of the road characteristics to the desired functional classification.

1.1.1. THE CONCEPT OF OPERATING SPEED

The concept of operating speed is aimed to represent drivers' speed choice in real-world conditions. However, roadway infrastructures form a very complex system, in which environmental, cultural, and regulatory conditions may vary significantly from one region to another. The diversity of road conditions has conducted to different interpretations of operating speed, which has been associated with different quantities estimated through a broad set of models. Therefore, the operating speed definitions across the literature are not always uniform and often overlap, particularly in academic studies. Nevertheless, the definitions contained in a few reference manuals present an essential contribution to clarify the concept of operating speed.

The manual *A Policy on Geometric Design of Highways and Streets* (AASHTO's Green Book) [14] defines operating speed as "the speed at which drivers are observed operating their vehicles during free-flow conditions." This definition is broad enough to include any form of speed quantification, as long as it refers to unconstrained vehicles. However, the manual notes that the 85th percentile of the speed distribution (*V85*) is the most frequently used operating speed measure across the literature. In the case of roads where geometric and traffic conditions allow drivers to travel at their desired speed, AASHTO's Green Book states that drivers' speed choice may vary over a very wide range of values, which is often the case of two-lane highways. Therefore, this manual recommends that the selected design speed shall meet the expectations of the great majority of drivers, i.e., shall reflect a high percentile of the expected speed distribution. This recommendation is, then, consistent with the fact that most of the official and academic studies had opted by *V85* to represent operating conditions.

In the same vein, the Manual on Uniform Traffic Control Devices (MUTCD) [15] attributes a broad meaning to the concept of operating speed, defined as "a speed at which a typical vehicle or the overall traffic operates." According to this manual, the operating speed can be represented through the average, pace, or 85th-percentile speed.

The Highway Capacity Manual (HCM 2010) [13] defines the concept of free-flow speed (FFS) as "the theoretical speed of traffic (...) when density is zero, that is, when there is no presence of vehicles" or "the average speed of vehicles on a given facility, measured under low-volume conditions, when drivers tend to drive at their desired speed and are not constrained by control delay", i.e., approximately the 50th-percentile speed of free-flow vehicles. As it is acknowledged in the manual itself, FFS under low-volume conditions is compatible with the definition of operating speed provided by AASHTO's Green Book. The

HCM 2010 also recognizes that operating conditions are not always considered in the selection of design speed, suggesting that FFS may be adopted in such situations.

Therefore, reference manuals tend to propose all-encompassing definitions of operating speed. This is also the principle adopted in this research, with the operating speed being represented by any speed measure that is suitable to represent the speeds practiced by drivers in real environment. This definition is valid for both individual design elements and road segments, considering free-flow conditions in the former case and the effects of traffic in the latter case.

1.1.2. LIMITATIONS OF EXISTING SPEED MODELS

Extensive research activities on speed modeling have been conducted to date by academia and road authorities, resulting in a large body of published literature that allows to understand the concept of operating speed and its main drivers and provides a wide array of models to predict operating speed under different circumstances. TRB [1] and Fitzpatrick et al. [16] provide good reviews on operating speed modeling.

Models, however, as more or less sophisticated representations of the real world, always present some sort of limitation. The most relevant concerns presented by researchers about existing statistical models used to predict operating speeds are related to three main topics: models' applicability, models' formulation, and assumptions about driving behavior [1].

1.1.2.1. Limitations presented by the scope and applicability of models

The expertise in speed modeling accumulated over decades have shown that no single procedure is universally accepted. The diversity of road policies, design standards, and driving practices across the globe has led to the development of models that cope with the reality of different regions. The definition of the geographic coverage of each operating speed model typically results from a previous evaluation by the researchers of the trade-off between developing a more generic model, using data from a larger area, but potentially harming the model's accuracy, and pursuing a model that considers the specificities of a smaller area [17].

Real-world speed data required for model development may be provided by an existing database or purposely collected. In the former case, data is available immediately, but the researchers' intervention in the definition of the explanatory variables and the selection of sites and number of observations per site is limited to the existing database. In the latter case, data collection procedures may be customized according to the study's objectives, but restrictions related to time, costs, equipment and human resources are usually involved. Bearing in mind these problems, to ensure the model's intended applicability, the sample must be representative of the road conditions at the region to be covered. In this sense, researchers shall always use their best efforts to obtain a large modeling sample [1].

A possible way to enlarge the sample size is to increase the number of survey sites. The diversification of geometric characteristics within the modeling sample should also contribute to a broader range of calibration, eventually easing the model's applicability in different contexts. According to Fitzpatrick et al. [18], a diversified sample contributes to the estimation of a larger number of variables affecting operating speeds to a reasonable level of statistical significance. This principle may address some of the concerns raised in the literature about the preclusion of relevant road conditions in existing speed models. Particularly, researchers have stressed the need for a deeper study on the effects of vertical alignment and its combination with the horizontal alignment [16, 19], the weather conditions [16], and the differences between daytime and nighttime speeds [16, 20].

The other possible method to enlarge the modeling sample is to increase the number of speed observations per site. Misaghi and Hassan [19] noted that numerous studies use less than 100 observations per site, corresponding to the minimum value proposed by the HCM 2010 [13] for operating speed studies. This concern is particularly relevant when the modeling process involves speed data aggregation for each site, because the extraction of percentile speeds from a small number of observations may lead to an inaccurate representation of the speed distribution.

Regarding the models' scope, Fitzpatrick et al. [16] reported that the majority of the operating speed models for two-lane highways provides speed estimations of passenger cars at horizontal curves and relatively flat terrain. Therefore, the literature suggests the development of additional models for tangents [16, 21] and for heavy vehicles [16, 22]. In the latter case, the vertical alignment can play an important role because of the impacts that higher grades produce on truck speeds [13].

The primary focus placed on the development of speed models for individual design elements has relegated to a second plan the prediction of segment speeds, i.e., speeds estimated over a length of roadway. The greater allocation of resources to collect segment speed data, necessarily involving techniques of vehicle tracking or license plate recognition, has probably contributed to the lack of studies in this area. The academic community has developed some methods to estimate segment speeds with limited applicability, e.g., for urban links [23–25] or freeways [26–28], where it is easier to obtain data from existing road monitoring equipment. In the case of two-lane highways, only some reference manuals [11, 13, 29] contain procedures to estimate operating speeds, but usually avoid detailed explanations about their scientific support.

Another frequent problem that may affect the validity and applicability of speed models is the occurrence of bias-errors during data collection [19]. The most common one is the cosine error in speed measurements with radars placed at the roadside, causing by the deviation between the reading beam and the traveling direction. Additionally, drivers tend to slow down upon perceiving test equipment as speed enforcement. Then, operators should consider measures to disguise test equipment, bearing in mind that installing it further away from the travel lane will increase the cosine error. Finally, in manual speed measurements, the minimization of human error shall be a primary concern.

1.1.2.2. Limitations presented by the formulation of models

The most common mathematical formulation among operating speed models is represented by a linear regression between a specific percentile speed observed at the survey sites and a set of explanatory variables characterizing the road conditions. The aggregation of speed observations collected at each site in a single percentile value, corresponding, in most cases, to *V85* [14], reduces the variability of the modeling sample. According to Tarris et al. [30], while this may increase the fit of the regression function, the impacts of the explanatory variables may be either underestimated or overestimated. Modeling the entire speed distribution may help to overcome this problem [18, 30].

With the prevalence of *V85*-prediction models, practitioners face difficulties in finding tools to estimate other percentile speeds. In fact, *V85* may not always be the best operating speed measure for the intended application. For example, the average travel speed is usually the preferred measure in traffic management and routing.

Regarding design consistency evaluation through speed differentials between successive design elements, the literature identifies two main problems inherent to the formulation of speed models. First, some authors noted that *V85* tends to underestimate those speed differences [19, 31, 32]. Second, conventional linear regression models represent the operating speed as the sum of the individual effects produced by the geometric characteristics of the survey element, disregarding the characteristics of the upstream alignment. In other words, not only the speed at a given element is assumed as completely independent from the speed at the preceding element, but also possible interactions between the explanatory variables and the order of magnitude of the practiced speeds are ignored, which in many times, are not realistic assumptions. Thus, calculating speed differences between successive elements based on speed estimations ignoring the upstream effects can lead to biased results [33], and consequently, to an inaccurate evaluation of design consistency and safety conditions.

The literature contains only two models that support a speed distribution and allow the customization of regression equations to obtain different percentile speeds. The model presented by Figueroa Medina and Tarko [34] represents a linear combination of variables affecting the mean and the standard deviation of the speed distribution. The model developed by Hewson [35] is capable of predicting the variation of percentile speeds over time, based on existing speed data, reflecting drivers' response to any intervention in the road system.

1.1.2.3. Limitations presented by erroneous assumptions about driving behavior

Many of the existing operating speed studies assume that drivers maintain a constant speed throughout a curve's entire length [19]. This principle simplifies data collection, because only one station per curve, usually placed at the midpoint, is required to measure speed. However, some authors have contradicted this assumption after observing speed variations within the curve limits [16, 19, 34]. Consequently, the representation of speed profiles with constant curve speeds and decelerations/accelerations occurring only on tangents at a constant rate is common, but may be unrealistic, potentially affecting the evaluation of safety and comfort parameters. Fitzpatrick et al. [16] recommends that additional research on acceleration and deceleration models should be conducted to increase the accuracy of speed profile representations. In this respect, these authors note that further studies on accelerations and decelerations should consider vertical alignment features or combinations of horizontal and vertical alignment.

1.2. RESEARCH PURPOSE AND OBJECTIVES

The complexity of the road system, materialized by different types of users interacting with each other under myriad geometric, environmental, and regulatory conditions, represent countless opportunities to improve the accuracy of the system's representation by models. The main purpose of this thesis is to present new models to enhance operating speed prediction capabilities in two-lane rural highways.

This study is aimed at using statistical methods to provide operating speed prediction models featuring innovative formulations and considering the speed effects produced by an unusually wide array of variables characterizing the road setting. Model development follows an integrated approach spanning from spot speed modeling to segment speed modeling. This approach allows gradually addressing some major gaps identified in the literature about speed modeling. The objectives of the research work in precise terms are listed below:

- Identify and quantify the effects on the operating speed produced by road geometry and roadside interference;
- Develop spot speed models for curves and tangents accounting for the road conditions at the element under consideration, the effects of recent driving experience and the expectations about the road ahead;

- Develop a segment speed model to assist practitioners in road design and operations management;
- Present flexible mathematical formulations to support estimations of any user-specified percentile speed in curves, tangents, and segments.

1.3. RESEARCH QUESTIONS

Taking into account the objectives outlined for this thesis and the gaps identified in the literature about operating speed modeling, the following research questions are formulated to serve as cardinal points around which the research is centered.

RQ1 What are the prerequisites to assume that a vehicle travels under free-flow conditions in a Portuguese two-lane rural highway?

RQ2 Which factors are relevant for drivers' speed choice?

RQ3 To what extent are spot speeds influenced by other conditions than those locally present at the site under consideration?

RQ4 How can model formulations evolve from traditional linear regressions to provide a better representation of the variability in drivers' speed choice and the interactions between speed and speed predictors?

RQ5 How can the development of a segment speed model benefit from the findings of previous spot speed research?

To answer these questions, this thesis presents a research methodology composed of six main steps. Each step is presented in the format of a scientific paper already published or submitted to a peer-reviewed journal. The decision of orienting this research toward the publication in peer-reviewed journals is aimed at increasing the visibility of the outcomes among the scientific community and practitioners, contributing to the progress of the state of the art and the state of the practice in a more effective way.

Each research question is addressed in one of more papers. The connection between the six papers and the five research questions is presented in Table 1, and thereafter, a brief summary of the papers is provided.

Table 1 – Mapping of papers and research questions

	Paper 1	Paper 2	Paper 3	Paper 4	Paper 5	Paper 6
RQ1	X					
RQ2		X	X	X	X	X
RQ3			X		X	
RQ4			X	X	X	X
RQ5						X

PAPER 1 *Free-Gap Evaluation for Two-Lane Rural Highways,* by A. Lobo, M. A. P. Jacques, C. M. Rodrigues, and A. Couto (2011)

Paper 1 consists of the assessment, for Portuguese two-lane rural highways, of the minimum time gap between two consecutive vehicles from which it is reasonable to assume that the speed of the following vehicle is not constrained by the presence of the leading vehicle, i.e., the following vehicle travels under free-flow conditions. The resulting free-gap value is subsequently used as a reference for the development of the spot speed models.

PAPER 2 *Road Cross-Section Width and Free-Flow Speed on Two-Lane Rural Highways,* by P. Melo, A. Lobo, A. Couto, and C. M. Rodrigues (2012)

Paper 2 describes a driving simulator study to evaluate the effects of road cross-section characteristics, specifically the lane and shoulder width, on the operating speed in two-lane rural highways. The need for this individual study arises from the observation of significant discrepancies among the literature about the consideration of such effects for speed estimation purposes. Interacting effects produced by the variation of lane and shoulder width are observed, i.e., the effects are not cumulative, and consequently, should not be considered individually.

PAPER 3 *Free-Flow Speed Model Based on Portuguese Roadway Design Features for Two-Lane Highways,* by A. Lobo, C. Rodrigues, and A. Couto (2013)

Paper 3 represents the first effort to model the operating speed under the scope of this thesis. In line with most of the existing research, the paper presents a free-flow speed estimation model corresponding to the 85th percentile of the speed distribution. The developed model is applicable for curves and tangents of two-lane highways, being calibrated for Portuguese roads classified as National Roads. This model successfully tests a distinctive exponential functional form, adopted to allow for the interaction between the effects of the explanatory variables and the order of magnitude of speed, denoting that speed varies proportionally with the independent variables. Additionally, the model demonstrates that spot speeds may be influenced not only by the local conditions at the survey site, but also by the characteristics of the upstream segment and the visibility to downstream, bringing together the effects of past and present driving experience and the expectations about the road ahead. The findings of this model serve as a basis for the following models.

PAPER 4 *Estimating Percentile Speeds from Maximum Operating Speed Frontier,* by A. Lobo, C. Rodrigues, and A. Couto (2014)

Paper 4 proposes a completely new approach to speed modeling: the operating speed frontier model (OSFM). The OSFM transposes to the field of speed modeling the formulation and principles of stochastic frontier production models, used in econometric analysis. First, a deterministic frontier function is estimated by an exponential regression between spot speeds and on-site geometric characteristics. The estimation of the speed frontier uses the entire free-flow speed distribution, thus providing an estimation of the speed adopted by the fastest driver for each combination of the explanatory variables. Then, the estimation of percentile speeds is possible through the cumulative distribution of the asymmetric disturbance. This disturbance term is always negative and accounts for non-quantified factors influencing speeds, such as the diversity in driving behavior, vehicle technology, and road environment. The model developed in this paper is also calibrated for Portuguese National Roads.

PAPER 5 *Flexible Stochastic Frontier Approach to Predict Spot Speed in Two-Lane Highways*, by A. Lobo, A. Couto, and C. Rodrigues (2016)

Paper 5 is aimed at improving the model developed in Paper 4 and enlarging its scope of applicability. The OSFM for National Roads is upgraded to account for the effects of the upstream segment and the visibility to downstream within the deterministic speed frontier. In parallel, the database is enlarged to include sites from two-lane highways classified as Complementary and Principal Itineraries, giving origin to a model specifically developed for both of these road categories. Together, the models developed in this paper are capable of supporting operating speed estimations in roads with design speeds ranging from 40 to 90 km/h.

PAPER 6 *Speed Prediction in Segments of Two-Lane Highways*, by A. Lobo, M. Amorim, C. Rodrigues, and A. Couto (2017)

Paper 6 presents an OSFM for segments of Portuguese National Roads. The segment speed model can be seen as an evolution of the spot speed model developed in Paper 5 for the same road category, incorporating the same relation between the segment characteristics found on the spot speed model and adding the influence of traffic. The new model is the only existing segment speed model for two-lane highways developed outside the scope of official guidelines, with the advantage of being capable to predict any desired percentile speed.

1.4. RESEARCH SCOPE AND LIMITATIONS

The main outcomes of this research consist of four spot speed models and one segment speed model for two-lane highways, calibrated for Portuguese conditions. As a result of the evolutionary approach followed in model development, described in the previous section, each model presents new features and/or enlarged applicability over its predecessor. The set of delivered models cover the following applications:

- Estimation of spot speeds in curves and tangents belonging to roads of different categories, according to the Portuguese classification, i.e., National Roads, Complementary Itineraries, and Principal Itineraries;

- Estimation of segment speeds in National Roads;

- Estimation of any user-specified percentile speed.

The models have the potential to assist practitioners in a broad range of applications spanning from road design to operations management, including design consistency analysis, speed limit definition, accident prediction modeling, evaluation of the level of service, travel time and cost, routing, and assessment of environmental impacts. In this sense, the segment speed model may be a particularly relevant instrument, since an approach-by-segment is followed in many of the referred applications, and only a few segment speed tools are provided in the literature.

In Portugal, both the spot and segment speed models delivered by this research may contribute to consolidate the role of operating speed in the future of design of two-lane rural highways, currently limited by the guidelines in force [12]. The applicability of the estimated models outside the Portuguese context shall be taken with caution, especially in non-European countries where road design standards and driving culture may be significantly different. Nevertheless, the methods and formulations adopted in this study are sufficiently versatile to be replicated by practitioners across the globe for a broad range of road conditions. Ultimately, the following entities may benefit from the outcomes of this research:

- Road managers, represented by national and regional governments, state companies, municipalities, and private concessionaires;

- Designers and planners;

- Society as a whole, as the user of the road system.

An extensive and resource-consuming data collection campaign is implemented to support the development of the models proposed in this thesis. The database contains more than 23,500 vehicles observed in seven two-lane highways. Therefore, to avoid an even more burdening data collection campaign, the following lines of research, representing limitations of the existing operating speed models, are not addressed in this study:

- Estimation of the operating speed during the nighttime;
- Estimation of the operating speed under adverse weather conditions;
- Estimation of the operating speed of heavy vehicles;
- Acceleration and deceleration modeling.

Additionally, this research does not deliver a segment speed prediction model for Principal and Complementary Itineraries in Portugal. The vehicle probe database, used to develop the segment speed model for National Roads, does not contain speed observations matching the Principal and Complementary Itineraries for which the design specifications are available.

1.5. THESIS OUTLINE

This thesis consists of eight chapters. Chapter 1 herein provides background information for understanding the relevance of this research and its contextual perspective, presents the research objectives and questions, and details the scope and limitations of the developed models. Chapters 2 to 7 present six scientific papers published or submitted to peer-review journals, corresponding to the six main steps composing the methodological approach. Chapter 2 presents a study to evaluate the establishment of free-flow conditions in Portuguese two-lane rural highways. In Chapter 3, a driving simulator study is conducted to evaluate the effects of the road cross-section on the operating speed. Chapter 4 presents the first spot speed model developed under the scope of this research, consisting of an exponential model to predict the 85th percentile speed in Portuguese National Roads. Chapter 5 introduces the OSFM formulation, with a spot speed model for National Roads capable of supporting estimations of any percentile speed. In Chapter 6, two new OSFM are developed, considering additional effects and enlarging the scope of applicability to Principal and Complementary Itineraries. Chapter 7 presents a segment speed model for National Roads, accounting for infrastructure and traffic conditions. Finally, Chapter 8 provides the main findings and contributions of this research, as well as suggestions for future work.

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FREE-GAP EVALUATION FOR TWO-LANE RURAL HIGHWAYS

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FREE GAP EVALUATION FOR TWO-LANE RURAL HIGHWAYS

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ABSTRACT

Studies related to operating speed predicting models' development require vehicles' speed under free-flow conditions to be collected at different sites. Thus, a critical issue is the definition of the gap (or headway) from which the speed of one vehicle is not affected by the speed of the vehicle ahead. In many studies, a 5-s headway was adopted as the reference headway value from which a vehicle could be assumed to travel at a free-flow speed. Justifications for this value's application are not clearly presented in the literature, and some authors suggest the use of other reference values. This paper presents a definition for platoon from observed values of vehicles' time gap. The reference gap value between two successive vehicles considered as traveling in a non-platoon condition is defined as "free gap." A five-step methodology is described and tested for road conditions in Portugal. The application performed showed both the adequacy of the methodology proposed and the convenience of exploratory studies aimed at the identification of platoon gap (or headway) suitable for specific operating speed studies. According to the methodology proposed, a 6-s gap is a suitable reference for future data collection on operating speed on Portuguese roads. This result suggests the need to review the headway reference values found in the literature for representing free-flow general conditions.

INTRODUCTION

Studies related to estimating operating speed for two-lane rural highways were performed in many places at different times. The term "operating speed" has changed in meaning over the years (*1*). A commonly adopted definition in studies of two-lane rural highways is that proposed by AASHTO (*2*), according to which the operating speed is the speed chosen by drivers during free-flow conditions. In this sense, it reflects the driver's response to road geometric and environmental characteristics because the driver is not affected by the presence of other vehicles. Operating speed is also affected by driving general practices and culture as well as by vehicle technology. For this reason, operating speed prediction models have been developed in different countries and, in many countries, have been developed in different regions and times. Knowledge of operating speed and its road-related factors is important for many traffic engineering activities, such as road safety analyses, speed limit definitions, and highway design consistency studies.

Operating speed is most frequently represented by the 85th percentile speed (V_{85}) of vehicles passing at a given road location, in a non-platoon condition, and it is usually determined by spot speed measurements. The *Highway Capacity Manual* (HCM) 2000 recommends that the number of observations for V_{85} calculation be equal to or greater than 100 (*3*). Therefore, one critical issue for studies of operating speeds is to define when a platoon condition is present. Another relevant question is related to the identification of the road volume for which the number of vehicles in a non-constrained operation is enough for V_{85} estimation.

In most studies on the development of operating speed prediction models, a non-platoon condition is usually defined by means of minimum headway between successive vehicles in a traffic stream. However, these studies do not describe the procedure adopted to establish the reference value taken. Also, this traffic measure is affected by the type of the two successive vehicles considered. Equipment available for automatic speed data collection is, in some cases, able to collect headway and gap values simultaneously. The gap between two successive vehicles, being the interval between the rear bumper of the first vehicle and the front bumper of the second as the vehicles pass a point on the roadway, is not affected by the vehicles' type. Therefore, the definition of platoon condition based on gap values can be useful for general applications.

In this context, this paper aims to present and test a procedure to define a gap value between two successive vehicles from which the vehicles can be considered as traveling in a non-platoon condition. This reference value is referred to as "free gap." In addition, the procedure allows for the identification of the traffic volume suitable for ensuring the sample size required for V_{85} measurements. Therefore, the procedure is proposed as the initial activity to be performed for V_{85} data collection for operating speed evaluation and modeling.

This paper is organized into five sections. After this introductory section, a brief literature review is presented on headway reference values considered for platoon definition in different operating speed studies. The third and fourth sections describe, respectively, the procedure proposed and its application to Portuguese conditions. This application is the initial step for a broad operating speed data collection activity planned to be performed at Portuguese roads for the development of a respective operating speed prediction model. The last section presents this study's main conclusions.

PLATOON DEFINITION FOR OPERATING SPEED MEASUREMENTS

Although there is not one definition for platoon, this term is commonly applied to a group of vehicles traveling together in which the vehicles behind the leading vehicle are usually not at their desired speed. That is, the following vehicles are experiencing some travel delay. Platoons are formed on two-lane, two-way rural highways because of difficulties in overtaking maneuvers caused by geometric features, opposing traffic, or both.

Operating speed measurements need to consider the speed of vehicles traveling at free-flow conditions and, therefore, during the speed data collection procedure, it is important to recognize vehicles in platoons. One fixed parameter used for this purpose is the time headway, from which it can be assumed that the following vehicle is not delayed by the leading vehicle. In the HCM 2000, this headway is established for two-lane highways as 3 s, whereas in previous versions of the manual, it was defined as 5 s (*3*). In both cases, no strong reasons are given for the value considered. Other authors, such as Guell and Virkler (*4*), have indicated different values of headways to constitute delay on two-lane highways. These authors, on the basis of theoretical considerations regarding deceleration rates and on speed of leading and following vehicles, found that headways of 3.5 s or 4.0 s might be suitable for this purpose. Gattis et al. reviewed different studies in which the headway time used to define delay at two-lane highways varies from 3.5 s to 6 s (*5*).

Studies conducted in different countries aimed at determining operating speed usually adopted the headway of 5 s as the reference headway to characterize a vehicle traveling under free-flow conditions. This is the case, for instance, in research by Fitzpatrick et al. (*6, 7*), Crisman and Perco (*8*), and Abdul-Mawjoud and Sofia (*9*). None of these studies describes the approach adopted to identify this headway value as the headway associated with free-flow vehicles on two-lane highways. One study pertaining to this question, although it applied to urban traffic, was developed by Vogel (*10*). The author proposed a methodology for identifying the headways associated with free-flow vehicles in urban areas, the application of which produced headways greater than 6 s.

The headway concept is concerned with the time interval between the passage of two successive vehicles at a point on the roadway, usually observed for the front bumper of both vehicles. Also, in considering the commonly adopted definition for gap as the time between vehicles measured from the rear of a vehicle to the front of the following vehicle, the relationship presented in Equation 1 applies. In this equation, for the sake of simplicity, it is assumed that the headway is measured by the passage of the front bumper of both vehicles.

$$h_i = g_i + \frac{l_{i-1}}{v_{i-1}} \tag{1}$$

where

h_i = headway of vehicle i (s),
g_i = gap of vehicle i (s),
l_{i-1} = length of the leading vehicle (i – 1) (m), and
v_{i-1} = speed of the leading vehicle (m/s).

It is important to highlight that the gap parameter value is not affected by the type of the leading vehicle (expressed by its length) or by its speed. The headway parameter, on the contrary, reflects both the length and speed of the leading vehicle. Therefore, its value must be considered in a more contextualized situation.

The need for extensive operating speed data collection for developing operating speed prediction models requires a suitable definition for the free-flow headway (or free-flow gap). This definition guarantees that the speed values of only non-platoon vehicles are taken into account and also prevents free-flow vehicles from being excluded from the sample. For this matter, it is convenient to perform a separate study in some highway sections with general features representative of the sections to be included in the final work. A methodology for doing so is presented next.

METHODOLOGY PROPOSED

The definition of a free-flow condition for the purpose of operating speed measurement can be done by means of both parameters: headway and gap. Usually the headway tends to be used, especially because of its relative simplicity for direct measurement in the field, in relation to gap observations. However, some available equipment for spot speed measurement in loco can provide both measures. The methodology was developed to deal with gap measurements. The advantage of using gap instead of headway is because the first is not affected by the leading vehicle's length and speed and, therefore, is a more representative global measure for platoon characterization.

This methodology has two main purposes: (*a*) definition of the gap value from which a vehicle may be considered as operating under free-flow conditions (referred to here as free gap); (*b*) identification of volume levels in an unconstrained traffic situation from which it is possible to obtain a sample of 100 or more vehicles for the sake of operating speed calculations (V_{85}). This is important because time and financial constraints require that data collection in each specific location should be as short as possible and still guarantee the quality of operating speed measurements. Therefore, the main idea underlying this work is to limit speed data collection over long time periods to a few representative locations. From the findings, faster and accurate extensive data collection activity can be performed, ensuring that only free-flow vehicles will be considered to provide operating speed values.

Step 1: Selection of the Sites to Be Studied

First, it could be assumed that free-gap values vary from one site to another. However, in terms of future operating speed studies, it is convenient to adopt a gap value suitable to all situations or at least to group road section types, such as tangents and curves. Subsequently, sites representing the overall sites' main traffic and road characteristics to be further analyzed must be selected.

Step 2: Operating Speed Evaluation Versus Gap Values

To make a large number of valid observations of both traffic directions on the sites selected, speed data collection should be performed over approximately 6 consecutive hours of non-congested traffic. Gap and speed values for each vehicle are recorded and treated. The gap values given by the equipment used come down to hundredths of a second. For this step, gap values less than 0.50 are rounded to zero, values from 0.50 to 1.49 are rounded to 1, and so on. With a view to estimating the gap value from which the vehicles could be unimpeded, for each rounded gap value (g_i), the V_{85} corresponding to vehicles with gaps greater or equal to g_i is calculated and plotted along a graphic form (Figure 1).

The visual analysis of the produced graphs allows for initial considerations of the effect of gap values on the operating speed for each case. In uncongested traffic, gap values from which V_{85} reaches stable values indicate that the vehicle's speed is likely to not be more affected by the gap value and, as a result, by the presence of the vehicle ahead. Given the methodology proposed, it is assumed that the smallest gap value from a sequence of four or more gaps with the same V_{85} values (FGS) belongs to the set of candidate gaps from which the free gap will be selected, as well as the gaps higher than the same. This set is said to form the graph region termed as "initial free-gap region." On the contrary, the highest gap value for which the graph shows a systematic V_{85} growing (NFG) is assumed as the initial upper limit of the set of gaps not related to free-flow operations. This set, therefore, is said to form the graph region named as "initial non-free-gap region." These regions are shown in Figure 1, and were defined for the purpose of the analysis referred to in Step 3. The graph region between NFG and FGS contains the gap values that it is not possible to classify a priori into non-free-gap and free-gap regions. Naturally, only after the definition of the free-gap value is it possible to identify the actual non-free-gap and free-gap regions.

Step 3: Correlation between the Speed of the Leading and Following Vehicles

If a vehicle is traveling in a free-flow condition, its spot speed is not affected by the speed of the preceding vehicle. Again, in taking into account the rounded gap values defined in Step 2, the correlation between each vehicle's spot speed (*Vn*) and the spot speed of the respective vehicle ahead (*Vn*-1) is determined (simple linear regression analysis). Graphs showing the correlation between vehicles' speed and gap value are constructed. The analysis is then conducted in a similar way to that adopted by Vogel for free headway definition for urban roads (*10*). The major difference is that the aforementioned author arranges the regions in free and non-free headways according to considerations regarding the correlation values themselves. For the present methodology, this is done on the basis of the results generated from Step 2. Two linear regressions for correlation values versus gap values are built (Figure 1). The first linear regression considers the correlation values for gaps less than and equal to NFG, and the second one for gaps greater than and equal to FGS. The gap value corresponding to the intersection point of the two previously mentioned linear functions represents the free gap for the situation studied. Hence, the correspondent correlation value for this gap can be calculated.

Although no specific correlation value can be established a priori, it can be assumed that correlation values under 0.30 mean weak correlations (*11*). However, the selected point could present a higher correlation value, which could be explained by the differences in approaching behavior caused by factors not related to the driver's desired speed, such as road geometry and traffic volume. Therefore, for correlation values greater than 0.30, the free gap will only be estimated at Step 4. If the gap value corresponding to the correlation equal to 0.30 is higher than the FGS defined in Step 2, the former value is assumed to be the new FGS. Thus, establishing a correlation equal to 0.30 for FGS leads to a wider range for the region between NFG and FGS.

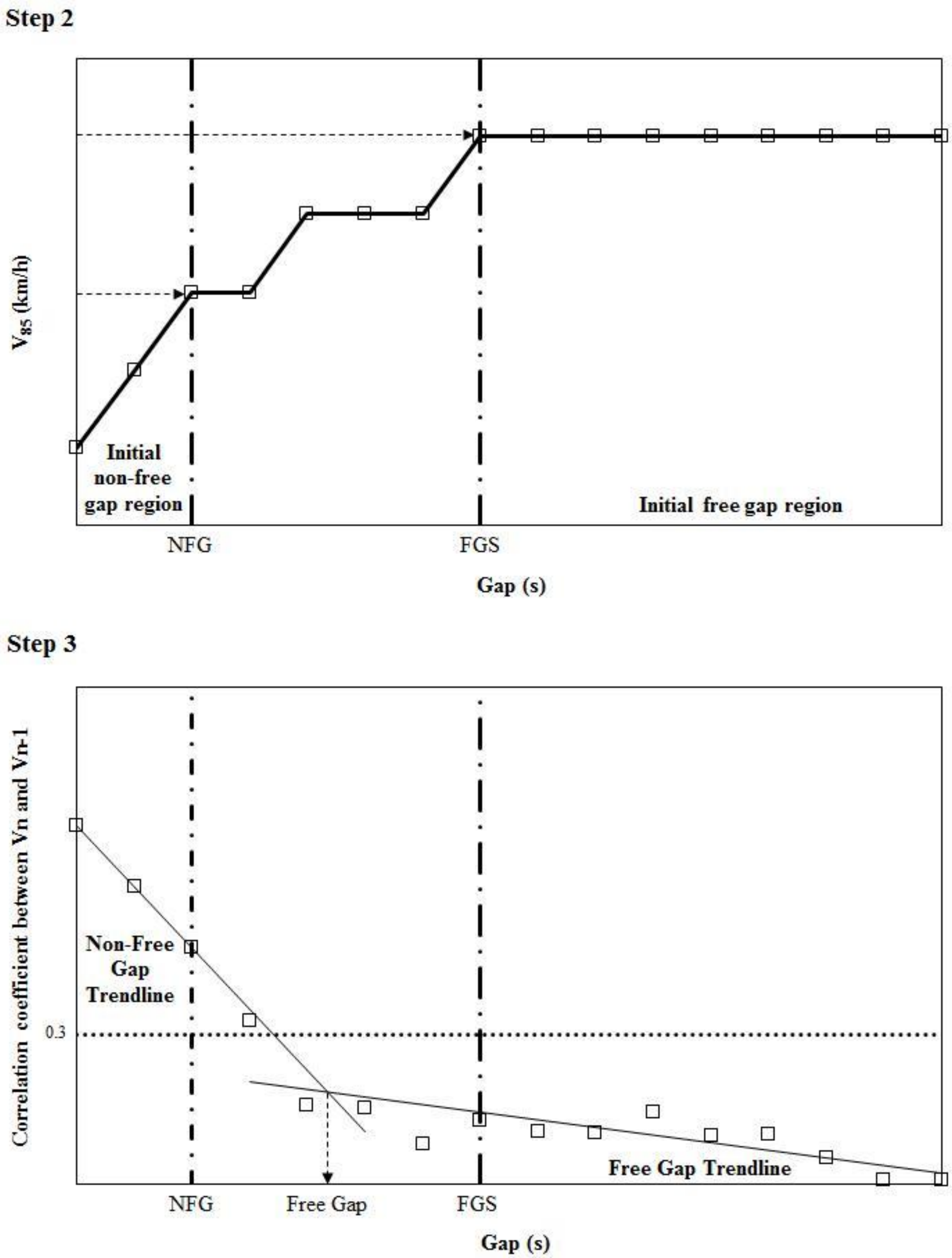

FIGURE 1 Methodology proposed: Steps 2 and 3.

Step 4: Gap Value and the Probability of Equal Leading and Following Vehicles' Speeds

This is the final piece of free-gap analysis. It aims to identify the probability of the following vehicle's speed not being equal to the leading vehicle's speed. As criteria, it is assumed that (*a*) following vehicles with gaps equal to or smaller than NFG are at non-free-moving conditions; (*b*) following vehicles with gaps equal to or greater than FGS are free-flow vehicles; (*c*) for the region between NFG and FGS, successive vehicles' speed is effectively different if the speeds differ from each other by more than 10% of the vehicles' average speed value (10% represents the maximum error, which is usually assumed at spot speed data collection); (*d*) for the observations mentioned at (*c*), following vehicles with speed different from the speed of leading vehicles can be taken as being at a free-flow condition and are classified as free-moving vehicles.

In this way, observations are divided into two categories: free- and non-free-moving vehicles. Non-free-moving vehicles are considered at the same speed as the vehicle ahead. On the basis of this division, a new categorical binary variable can be created. This variable (*Y*) will be made equal to zero for non-free-moving vehicles and one otherwise. With this variable in mind, it is possible to evaluate the association between free-moving vehicles and vehicles' gap. The dichotomous nature of the dependent variable facilitates the application of binary logistic regression, for which the probability of being in platoons against free-moving vehicles is estimated by a maximum likelihood method.

In this logistic regression model, the latent variable is formulated by Equation 2.

$$f(x) = \beta_0 + \beta_1 \cdot x \tag{2}$$

where x is ln(gap) and β_0, β_1 are regression coefficients.

The natural logarithm of the gap variable values is used for allowing normal distribution of the model's independent variable (x).

With this latent variable, the conditional probability of a positive outcome (free-moving vehicles, $Y = 1$) is determined by Equation 3:

$$Prob(Y = 1 \mid x) = \frac{\exp\left(f(x)\right)}{1 + \exp\left(f(x)\right)} \tag{3}$$

The resulting model, calibrated for each site, is then used to calculate (*a*) the probability of free-moving vehicles for the free gaps selected in Step 3 (probability values above 0.50 provide a strong indication on the suitability of the previously selected gap to represent the free-flow conditions for the sites under analysis); and (*b*) the free-gap values for the situations that revealed high correlation values (>0.30) for the intersection point of the linear regressions
performed in Step 3. In the latter cases, the free gaps are defined by $P(Y = 1) = 0.50$.

Step 5: Volume Level Suitable for Data Collection

As stated before, if the operating speed study includes many road locations, it is desirable to have some guidelines to define the number of hours over which speed data must be collected for the minimum of 100 speed observations to be reached. The number of different possible values of gap presented in a traffic stream depends strongly on traffic volumes.

By disaggregating the total data collected along the overall observation period in hourly volumes, it is possible to identify the number of the total hourly gaps that are equal to or greater than the free gap defined in the previous steps. That is, it is possible to identify specific volume levels per direction in an uncongested traffic condition that are enough for V_{85} determination.

APPLICATION PERFORMED

The application of the methodology was planned as the initial activity in developing an operating speed prediction model for Portuguese roads. It was performed as follows. Because the application of Step 5 has no special features, it will not be detailed here; only the final results are presented.

Site Selection

The field study was conducted on an 11-km-long section of the road N 222, located in Porto’s environs. The average cross-section is formed by two 3.60-m-wide lanes and two 2.30-m-wide shoulders. Data collection was performed at four sites with different geometric characteristics: two sites are located in tangents and two in horizontal curves. One of the chosen sites in tangent is 240 m long with a grade of 2.6%; the other is 513 m long with a grade of 1.9%. Regarding the chosen curves, one has a radius of 220 m, with a length of 360 m and a grade of 6.0%; the other has a radius of 545 m, with a length of 221 m and a grade of 2.6%.

The 513-m-long tangent had a posted speed limit of 70 km/h. There were no signs for the local speed limits at any of the other sites. Therefore, the Portuguese speed limit of 90 km/h for two-lane rural roads applies.

The pavement along the whole extension of the road section studied was considered to be in good condition.

Data Collection

The data were collected and recorded with traffic counting devices, consisting of a Doppler radar sensor with an integrated Flash RAM data memory and a real-time clock. Data download is performed by connecting these devices to a computer, either by means of a serial or a Bluetooth.

The traffic counters were placed approximately at the midpoint of the selected tangents and curves, with the lighting poles on the roadside to fix the equipment. The average mounting height of 2.5 m and the traffic counters’ position were selected to avoid biased behavior by drivers. This precaution was taken because drivers tend to brake given when they see unfamiliar objects installed on the roadside.

Data collection was performed under clear weather conditions (dry pavement) and for a period of 12 h (between 8:00 a.m. and 8:00 p.m.) to evaluate the hourly traffic volumes between the morning and the afternoon peaks. Not even at peak hours did the traffic reach a congested level.

Data Description

A database was constructed for each site, containing each vehicle's passing time (hh:mm:ss), speed, and gap to the vehicle ahead.

Previous tests with the same traffic counters revealed that these devices detect and register the presence of pedestrians. To remove pedestrians from the collected databases, all observations with recorded speeds beneath 10 km/h were deleted. Therefore, the gaps for the following observations had to be recalculated. Pedestrian activity is usually low in rural areas, and the road section studied is not an exception. The data loss caused by pedestrian elimination was smaller than 0.1% of the total number of observations. Further, because the overtaking vehicles may have had very small gap values captured by the devices, an exploratory analysis was initially performed to verify whether for the gaps less than 0.5 s the speed differences between leading and following vehicles made sense in a platoon condition. For all studied sites, more than 35% of the following vehicles registered a greater speed than leading vehicles, sometimes with values higher than 10 km/h. For this reason, the gap value equal to zero was not included in studying the free gap.

For both directions in each site, the average and the standard deviation values of recorded hourly traffic volumes and speeds are presented in Table 1. These values reflect the database before the records of gap values less than 0.5 s were removed.

TABLE 1 General Data on the Sites Selected

Data Description	Tangent 1	Tangent 2	Curve 1	Curve 2
	Length = 240 m Grade = 2.6%	Length = 513 m Grade = 1.9%	Radius = 220 m Length = 360 m Grade = 6.0%	Radius = 545 m Length = 221 m Grade = 2.6%
Number of vehicles	7,156	10,637	8,503	6,637
Bi-directional hourly volume (vph)				
- Average	596	886	709	553
- Standard deviation	132	237	186	147
- Minimum	430	564	452	359
- Maximum	835	1331	1063	790
One-way hourly volume (vph)				
- Average	298	443	354	277
- Standard deviation	77	152	115	78
- Minimum	197	280	200	173
- Maximum	499	904	718	473
Speed (km/h)				
- Average	73.3	67.7	63.8	72.0
- Standard deviation	15.7	14.4	14.2	15.5

Free Gap Definition

Steps 2, 3, and 4 of the methodology were applied for each of the four studied sites. To facilitate the comparative analysis, the results of the two straight segments for Steps 2 and 3 are presented in the same figures (Figures 2 and 3). In all figures, the gap value of 16 represents all records related to gaps greater than and equal to 16 s. The same was done for the two curved segments (Figures 4 and 5). Table 2 presents the major statistics and the equations related to the four logistic regression models, and Tables 3, 4, and 5 show the overall gap analysis results for all four sites studied.

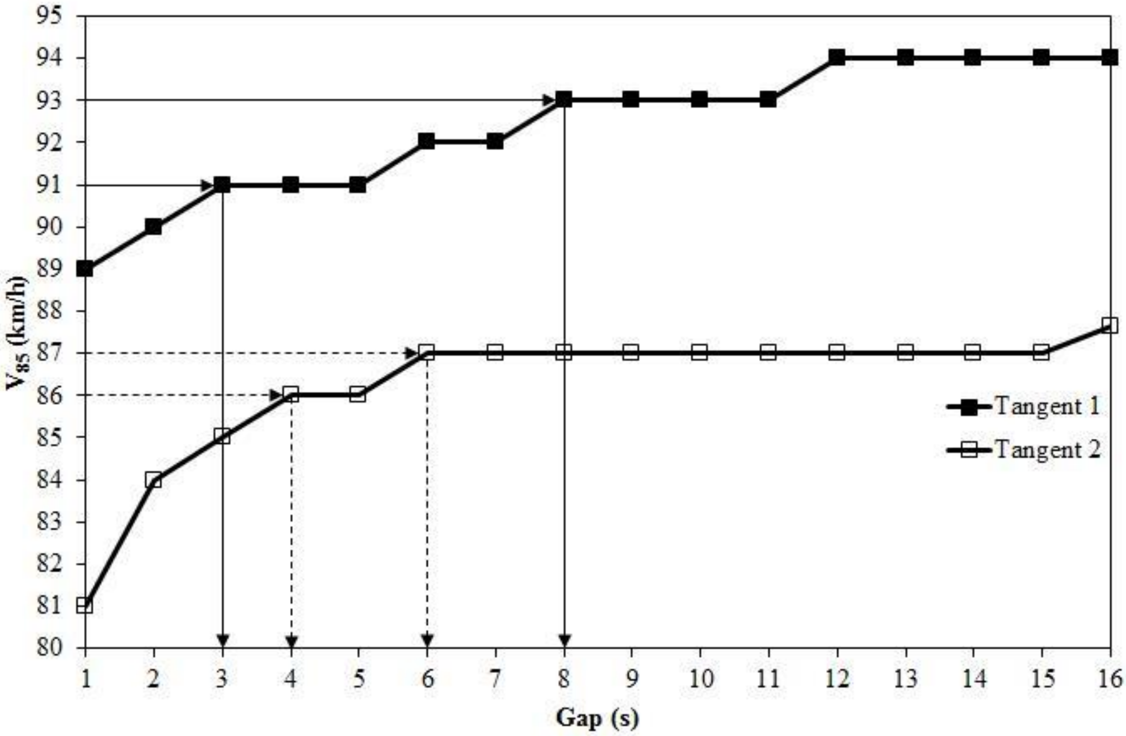

FIGURE 2 Results of Step 2 for the sites in tangent.

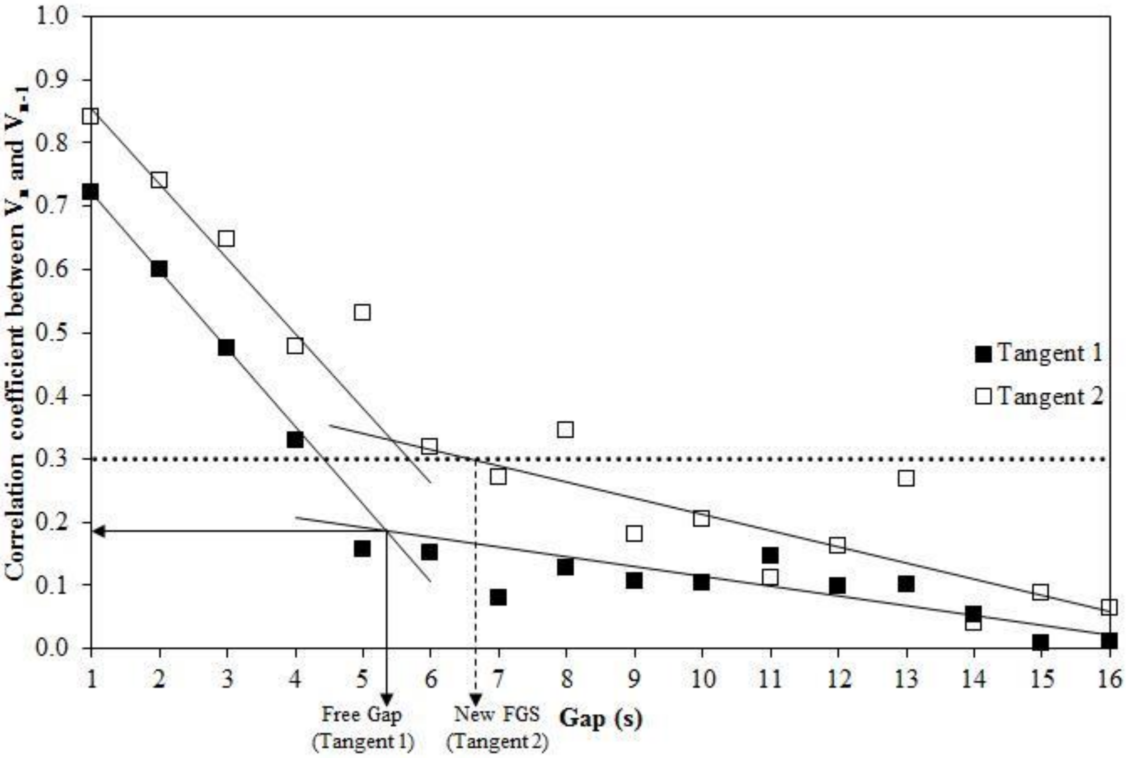

FIGURE 3 Results of Step 3 for the sites in tangent.

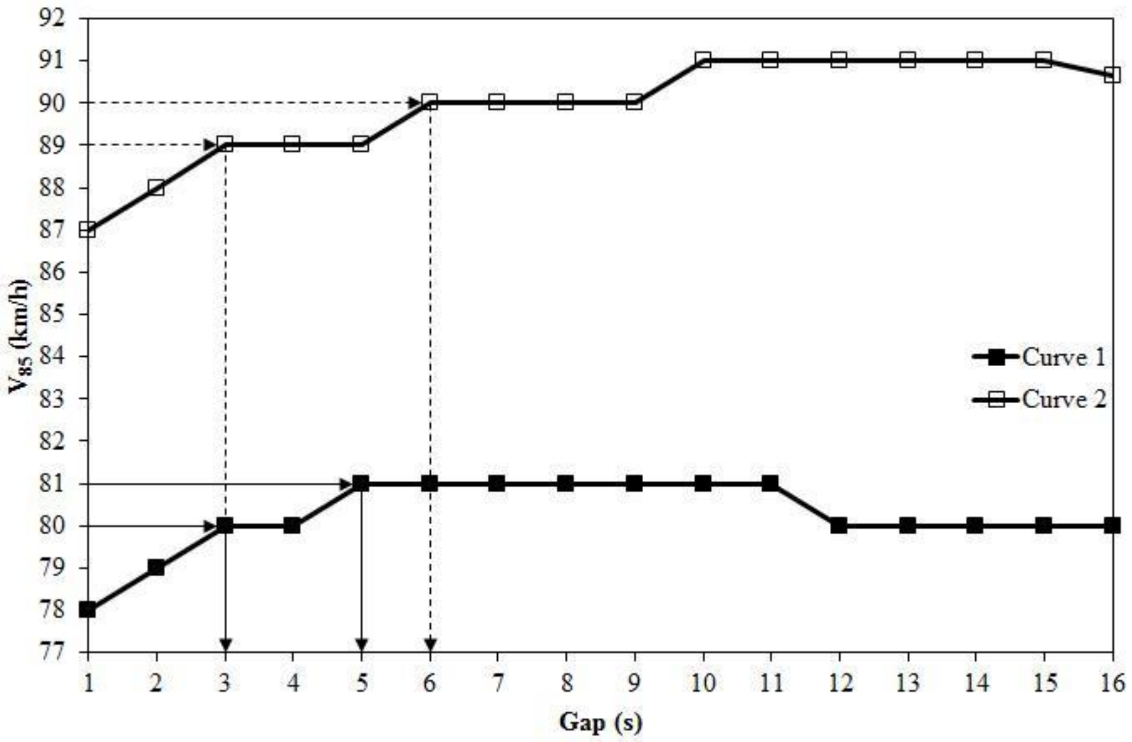

FIGURE 4 Results of Step 2 for the sites in curve.

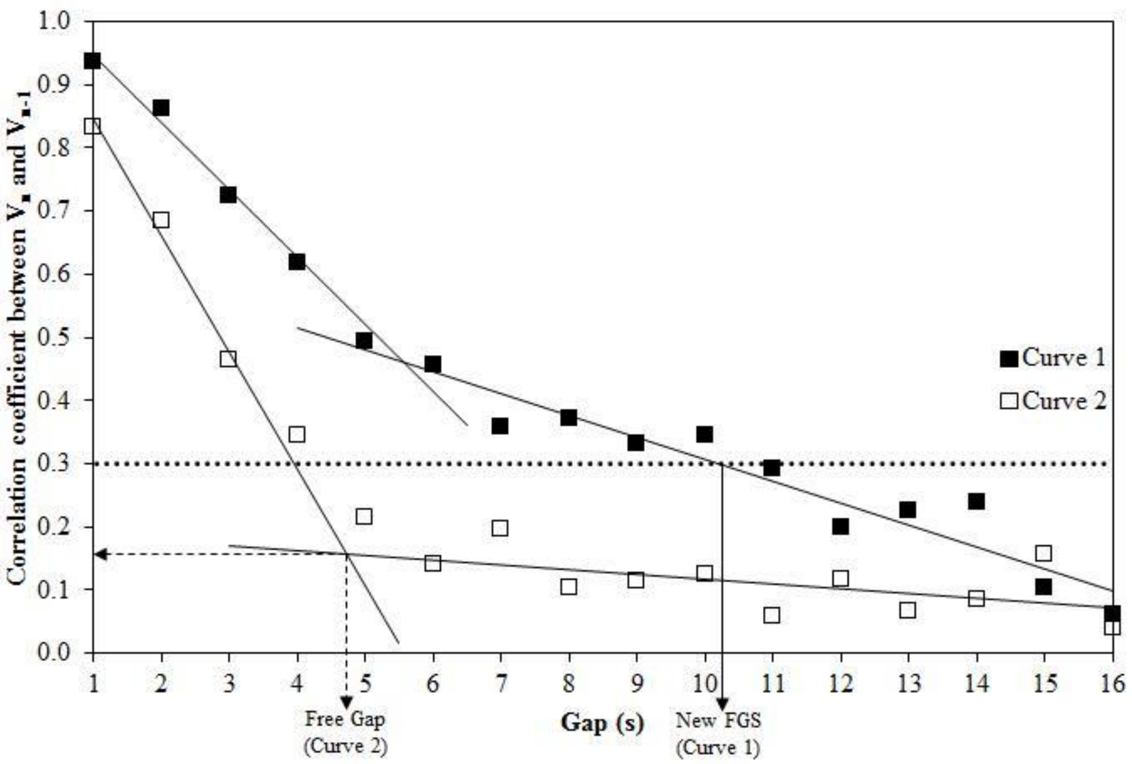

FIGURE 5 Results of Step 3 for the sites in curve.

TABLE 2 Logistic Regression Models

Site	Parameter	Estimated Value	Standard Error	P[|Z|>z]
Tangent 1	β_0	-5.986	0.183	0.000
	β_1	3.971	0.114	0.000
	Goodness of fit			
	Log-likelihood	-1,299.561		
	Number of observations	6,696		
Tangent 2	β_0	-12.523	0.412	0.000
	β_1	7.735	0.251	0.000
	Goodness of fit			
	Log-likelihood	-941.171		
	Number of observations	9,796		
Curve 1	β_0	-5.799	0.153	0.000
	β_1	3.426	0.086	0.000
	Goodness of fit			
	Log-likelihood	-1488.501		
	Number of observations	7,702		
Curve 2	β_0	-7.988	0.292	0.000
	β_1	5.609	0.197	0.000
	Goodness of fit			
	Log-likelihood	-816.839		
	Number of observations	6,232		

TABLE 3 Summary of Results from Step 2

Site	Non-Free-Gap Region		Free-Gap Region	
	Initial Gap (s)	Final Gap (s)	Initial Gap (s)	Final Gap (s)
Tangent 1	1	3	8	16+
Tangent 2	1	4	6	16+
Curve 1	1	3	5	16+
Curve 2	1	3	6	16+

TABLE 4 Summary of Results from Step 3

Site	Non-Free-Gap Region		Free-Gap Region		Free Gap	
	Equation	R^2	Equation	R^2	Value	Correlation
Tangent 1	Y=-0.1229X+0.8448	1.00	Y=-0.0153X+0.2673	0.72	5.4	0.19
Tangent 2	Y=-0.1179X+0.9712	0.98	Y=-0.0254X+0.4664	0.65		> 0.30
Curve 1	Y=-0.1068X+1.0550	0.97	Y=-0.0347X+0.6542	0.92		> 0.30
Curve 2	Y=-0.1846X+1.0306	0.99	Y=-0.0075X+0.1929	0.30	4.7	0.16

TABLE 5 Results from Steps 3 and 4 and Complementary Analysis

Site	Step 3		Step 4			
	Free-Gap Value (s)	Free-Gap Range (s)	Free Gap (s)		P (Y=1) (%)	Rounded Free Gap (s)
Tangent 1	5.4		5.4	→	67.1	6
Tangent 2		]4;7[	5.1	←	50.0	6
Curve 1		]3;11[	5.4	←	50.0	6
Curve 2	4.7		4.7	→	66.7	5

Two observations arise from Table 5. The first is that the found free gap is not significantly different for each site, with the difference between the maximum and the minimum values being smaller than 1 s. If one considers the case of cars (about 4.5 m long) at the average speed value measured at each site, the corresponding free headways would be 5.6 s for Tangent 1 and Curve 1; 5.3 s for Tangent 2; and 4.9 s for Curve 2. In rounded values, these values are the same as the rounded gaps shown.

Moreover, in the cases of Tangent 2 and Curve 1, the application of Step 3 resulted in wider ranges for the regions between NFG and FGS, with the free gaps being obtained only at Step 4. In fact, higher speed correlations occurred for both sites, since Tangent 2 presents the higher average hourly volume of 886 vehicles per hour (vph) and Curve 1 presents the steeper grade of 6.0% (heavy vehicles may disturb traffic flow). However, the free gaps obtained at Step 4 for these two sites are similar to the values estimated for Tangent 1 and Curve 2, which may reveal that there are no relevant differences in drivers' approaching behavior.

Because the purpose of the application was to find a single rounded free-gap value covering the requirements for free-flow speed at all sites to be studied along Portuguese roads, the more conservative choice was to select the gap of 6 s as the free gap. This value was suitable for all the sites studied, and it may serve as a reference for future data collection on operating speed. This choice also does not require excessively long periods of field collection for most Portuguese rural roads. In future research on operating speed along Portuguese roads, the necessary validation of the selected value for other sites will be possible.

The free gap produced by this study, which led to a 6-s free headway, differs from the commonly used 5-s free headway. It is clearly different from the 3-s free-flow headway recommended by the HCM 2000 (*3*). This result implies that further international studies are also required.

Volume Evaluation

The application of the last step of the methodology proposed, considering the hourly volume data collected during the 12-h period studied, indicated that hourly volumes in the range from 250 to 500 vph were suitable for the data collection intended.

CONCLUSIONS

As for any type of highway, the definition of gap values, as well as headway values, associated with vehicles operating in free-flow conditions is an important issue for data collection planning focusing on operating speed measurements along two-lane, two-way highways. There is no consensus in the literature regarding the gap or headway value from which the free-flow conditions generally hold, given non-congested traffic flow situations. However, in many studies, 5-s headways have been used as a reference value for data collection on free-flow vehicles' speed, and it seems to be an underestimated value when compared with the 6-s free gap found in this paper. Most studies do not question the possible differences that may occur from site to site as a reflection of road geometry and from area to area (city, state, or country) as a function of general driver behavior.

Nonetheless, one cannot simply adopt a very high reference value that will cover the conditions of all possible sites and places. Because field data collection usually requires important technical and financial resources, it is essential to generate good quality data in the least amount of time possible. The assumption of very high gaps (or headways) for representing free-flow vehicles will imply longer data collection periods or will limit the collection period to hours of very low traffic flow. In both cases, the optimal use of available resources, especially automatic data collection equipment, cannot be achieved. The methodology presented in this paper seeks to cope with this situation by defining the gap value representing the free-flow speed situation (free gap) for a particular planned operating speed study.

The proposed five-step methodology was applied to estimate the free-gap values in four selected sites that present diverse geometric features (tangents with different extensions; curves with different radii and grades). The results indicate cohesiveness among the four sites, with free-gap values varying from 5 s to 6 s. Because the purpose of this study was to obtain a single rounded free-gap value as a reference for Portuguese two-lane rural roads, the selected free gap is 6 s. The results also show that the commonly used free-flow headway of 5 s effectively applies to some sites. However, the use of 5 s as a general reference must be reviewed, as well as the HCM recommended value, which was lowered from 5 s to 3 s after the review conducted in 2000 (*3*).

Further validation of the selected free-gap values calculated for Portuguese conditions is planned to be performed in the near future as part of the ongoing research on an operating speed prediction model for the country's two-way, two-lane rural highways.

ACKNOWLEDGMENT

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ROAD CROSS-SECTION WIDTH AND FREE-FLOW SPEED ON TWO-LANE RURAL HIGHWAYS

PAPER 2 Melo, P., A. Lobo, A. Couto, and C. M. Rodrigues. Road Cross-Section Width and Free-Flow Speed on Two-Lane Rural Highways. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2301, 2012, pp. 28-35.

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ROAD CROSS-SECTION WIDTH AND FREE-FLOW SPEED IN TWO-LANE RURAL HIGHWAYS

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ABSTRACT

Speed choice is strongly influenced by geometric road features. In this work, the influence of lane and shoulder widths on free-flow speed was studied with the driving simulator *DriS* at the University of Porto in Porto, Portugal. To evaluate how speed was influenced by the cross-section, this study investigated the possible influence of the order of magnitude of the practiced speeds on the effects of variations in lane and shoulder widths. Two types of roads with different base speeds were considered. The roads were presented to drivers on a driving simulator. The validity of the data obtained in the simulator was confirmed through a comparative analysis of the registered speeds in the real environments for the equivalent simulator conditions at six points of control. The lane and shoulder widths from which the free-flow speed was no longer conditioned by the dimensions of the road's cross-section were obtained, as well as the reduction in speed associated with smaller widths. Contrary to what was suggested by the *Highway Capacity Manual 2010*, the individual effects of variations in lane and shoulder widths were not cumulative; greater impacts on free-flow speed were obtained by their simultaneous variation.

INTRODUCTION

An important component in characterizing the service provided by a given highway is the free-flow speed (*1*), which represents drivers' speed choice under free-flow conditions. The free-flow speed reflects drivers' response to road geometric and environmental characteristics without the presence of vehicles ahead. The free-flow speed can be also affected by vehicle characteristics and general driving practices. According to the *Highway Capacity Manual 2010* (HCM) (*1*), the level of service for two-lane highways depends on the average travel speed, which in turn depends on the free-flow speed. When it is not possible to conduct the measurements required for calculating the free-flow speed, the HCM (*1*) proposes an estimation model in which some correction values representing road geometric characteristics are applied to a base free-flow speed. This model is represented by Equation 1:

$$FFS = BFFS - f_{LS} - f_A \tag{1}$$

where

FFS = free-flow speed,
$BFFS$ = base free-flow speed,
f_{LS} = adjustment parameter for lane and shoulder width (km/h), and
f_A = adjustment parameter for density of access points (km/h).

The base free-flow speed can be assumed as the speed observed for roads presenting the basic requirements of the geometric conditions suggested by the HCM (*1*): no access points and lane and shoulder widths equal to or greater than 3.6 m and 1.8 m, respectively. For smaller cross-sections and higher densities of access points, the HCM (*1*) proposes reductions in the free-flow speed. The reductions related to the width of the cross-section are presented in Table 1.

TABLE 1 Adjustment Factor for Reductions in Free-Flow Speed (km/h) According to Lane and Shoulder Widths (*1*)

Lane Width	Shoulder Width (m)			
(m)	≥0.0 to <0.6	≥0.6 to <1.2	≥1.2 to <1.8	≥1.8
2.7 to <3.0	10.3	7.7	5.6	3.5
≥3.0 to <3.3	8.5	5.9	3.8	1.7
≥3.3 to <3.6	7.5	4.9	2.8	0.7
≥3.6	6.8	4.2	2.1	0.0

Speed reductions presented in the HCM (*1*) are based on the findings of Harwood et al., presented in the final report of NCHRP Project 3-55(3) (*2*). In this report, a regression relationship between shoulder width reduction and speed reduction observed in a real environment was performed; it assessed the effects of lane width variation on free-flow speed on the basis of previous studies in the area. The values in Table 1 suggest cumulative effects on the free-flow speed from variations in lane and shoulder width (i.e., the reduction in speed for a given cross-section composed of a lane width smaller than 3.6 m and a shoulder width smaller than 1.8 m is the sum of the individual effects caused by each variable).

This paper contributes to the evaluation of the effects on the free-flow speed from road cross-section characteristics – lane and shoulder width – through a driving simulation study. The simulated environment allows the assessment of speed reductions for a greater number of cross-section combinations as well as the consideration of a wider range of lane width values than the methodology used in NCHRP Project 3-55(3) (*2*). In addition, the smallest cross-section from which the speed choice is no longer affected by the lane and shoulder widths is provided and compared with the HCM (*1*) proposals.

The establishment of free-flow conditions is defined by the time interval between two successive vehicles. The HCM (*1*) suggests that a 3-s headway is suitable for free-flow conditions, although this value is not unanimous among the literature. For example, a study of Portuguese two-lane rural roads by Lobo et al. (*3*) suggests a 6-s gap as the reference for free-flow conditions.

This study contributes to the knowledge of adequate cross-section characteristics for the desired speed of a given road. Several studies on road safety have referred to speeding as a major cause of car accidents (*4, 5*). Therefore, the road geometric features (the horizontal and vertical alignments and cross-sections) should suggest to drivers an adequate speed choice to promote road safety and the sustainability of the surrounding environment.

DATA COLLECTION

Experimental Approach

Studies of speed can be performed with different methodologies, such as the use of instrumented vehicles, naturalistic studies, real environment monitoring, or driving simulation, depending on the variables to be considered.

This study analyzed the average travel speed adopted for a set of road scenarios with different cross-sections. The use of a driving simulator allowed a high level of control over the variables (*6*). Therefore, it is the most suitable approach for studying changes in drivers' speed choice as a result of the variation of the characteristics of the cross-section.

The simulator used in this study was the DriS, which is a fixed-base driving simulator installed at the Traffic Analysis Laboratory of the Faculty of Engineering of the University of Porto in Porto, Portugal. Two roads near Porto (N 105-2 and N 222) were selected for this study. The design speeds of these roads are 40 km/h and 80 km/h, respectively, representing two types of roads: one more winding and the other less demanding for drivers. For each road, the road alignment of a 3-km-long section was collected by a GPS device installed in an instrumented vehicle. Then, both stretches were reproduced in the DriS to compare the influence of variations in the cross-section width on the free-flow speed of roads presenting different alignment standards. It was expected that the effects of the characteristics of the cross-section were greater for higher speeds.

The driving experiences conducted in the DriS were performed by 15 drivers. The group of drivers had the following characteristics: (*a*) 60% were males and 40% were females; (*b*) they ranged in age from 20 to 40 years; (*c*) each driver had held a driver's license for 3 or more years; (*d*) each driver drove at least 10,000 km per year, with 5,000 km on two-lane rural highways; and (*e*) they did not usually drive on the chosen roads. The 15 drivers were selected because they adapted well to the simulated environment and showed realistic driving behaviors.

The drivers drove the DriS across the simulated roads, composed of successive 3-km-long sections, each one presenting a different combination of lane and shoulder width. The characteristics of the horizontal alignment were kept the same. Smooth cross-section transitions between scenarios were ensured by intermediate 100-m-long tangent sections. The lane and shoulder widths are presented in Table 2.

TABLE 2 Cross-Section Scenarios Presented in Simulated Environment

Lane Width (m)	Shoulder Width (m)							
	N 105-2				N 222			
	0.3	0.8	1.2	1.8	1.2	1.8	2.2	2.5
2.7	9	8	10	12	9	8	10	12
3.0	7 (II; III)	1	2	11	7	1	2	11
3.3	4	3 (I)	13	15	4	3	13	15
3.6	6	5	16	14	6	5	16 (I; II)	14 (III)

Note: I, II, and III correspond to the cross-sections considered for validation with the real environment spot speeds.

The values considered for lane and shoulder widths were chosen according to the HCM (*1*) (Table 1) and according to the cross-section characteristics most commonly adopted on these types of roads. For each road, the 16 scenarios were driven in sequences of four to avoid driver fatigue. These sequences were chosen randomly to avoid excessive familiarity with the road alignment, and they were preceded by 5-km-long training stretches.

The realism of the simulated environment was improved through the introduction of trees at the roadside and of opposing traffic appearing in the same spot of the road for all the scenarios. The presence of vehicles ahead was not introduced in the simulated environment. In these conditions, the average travel speed corresponds to the free-flow speed.

The selected 3-km-long stretches were built on level terrain, with grades below 3% (*1*). Therefore, the effects of the vertical alignment were not considered in the simulator study. Moreover, no intersections, which could disturb drivers' speed choice, were present in the road sections under consideration.

In Figure 1, the simulation setting and screen are presented.

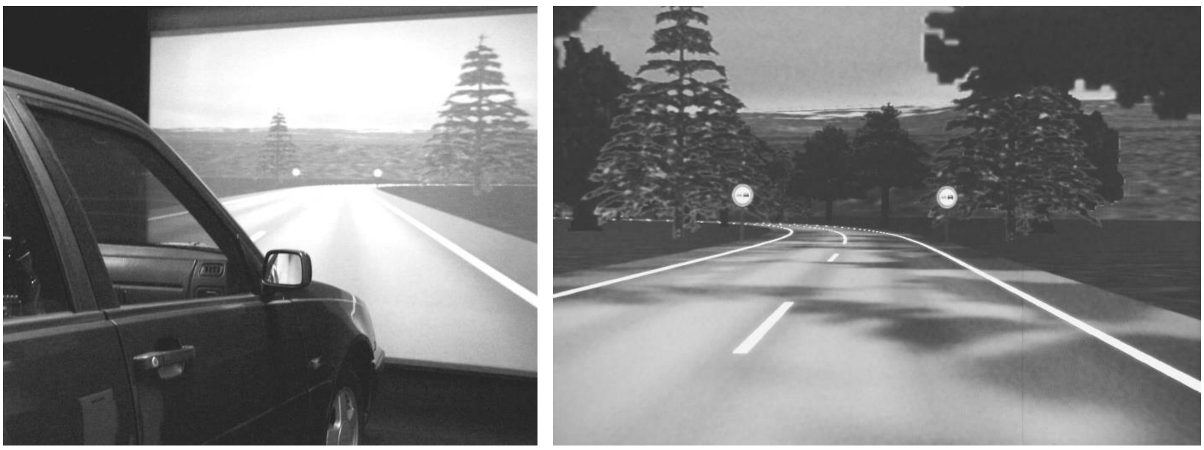

FIGURE 1 DriS simulation setting and screen.

Description of Variables

The variables considered in this study were evaluated using the vehicle's spatial and temporal location, collected by the DriS.

First, a set of three variables was considered to evaluate the quality of each experiment, removing drivers who had adopted unrealistic behaviors. Thus, using the registered number of times that drivers crossed the lane limits, two variables were created: the average percentage of road length driven crossing the centerline and the average percentage of the road length driven crossing the sideline. These variables are mutually exclusive, and their sum represents the average percentage of road length driven out of the lane limits. For both roads, the maximum driving error allowed for the drivers was approximately 30%.

The average distance to the centerline and the average distance to the sideline were estimated for a sensitivity analysis of the driver's behavior when faced with different cross-section widths. For this estimation, the distances registered out of lane limits were considered to be negative.

For the development of the regression model, the dependent variable was the free-flow speed obtained in the simulated environment, which is represented by the average travel speed estimated for each cross-section combination, with the length of the stretch divided by the average travel time observed for each driver.

The independent variables were lane width, shoulder width, the product of the lane and shoulder widths, and the dummy variables representing the different roads and drivers. The product of the lane and shoulder widths allowed the evaluation of the combined effects of both variables. The dummy variables for the roads allowed the inclusion of all gathered data into the same regression, increasing the number of observations. Otherwise, some combinations of lane and shoulder widths would be repeated without being distinguished by the road type. Dummy variables related to drivers express the individual driving behavior observed for each person when compared with a randomly chosen base driver. Thus, only 14 dummy variables for the drivers were considered.

Finally, the speed values obtained in the simulated environment were calibrated. Therefore, the average spot speed in the real environment was determined for three elements (tangents and curves) of each road. The same speed was then determined in the simulated environment for the same elements (with the same cross-section width), allowing the comparison between both environments.

METHODOLOGY PROPOSED

Regression Modeling

The proposed model assumes that the relationship between the free-flow speed and the independent variables is suitable to be represented by a power function that can be linearized by extracting the natural logarithm of the continuous variables, as presented in Equation 2:

$$\ln(FFS) = a + b\ln(l) + c\ln(s) + d\ln(l)\ln(s) + ed_r + \sum_{i=1}^{14} f_i d_{d\,i} \tag{2}$$

where

a, b, c, d, e, f_i = regression coefficients,
l = lane width,
s = shoulder width,
d_r = dummy variable for road type, and
d_{di} = dummy variable for drivers.

A multiple linear regression (the least squares approach) was performed with Equation 2 to estimate the effects of the cross-section on the free-flow speed.

Then, for each cross-section width and road type, the average free-flow speed value of the 15 drivers was estimated. The minimum cross-section from which the increase in lane and shoulder widths did not produce effects on the free-flow speed was considered the baseline scenario. This scenario serves as a reference for estimating the reductions in the free-flow speed for the geometric characteristics of narrower cross-sections.

Validation of Results

The road sections tested in the simulated environment were reproductions of real roads, allowing the results obtained in the simulator to be validated (*7*). The validation was performed through a comparative analysis of the spot speeds observed in the real and simulated environments at six points of control (represented in Table 2 by the numerals I, II, and III for each road).

In the simulated environment, spot speeds were automatically registered by the DriS. In the real environment, spot speeds were collected with traffic-counting devices, consisting of a Doppler radar sensor with integrated flash random access memory and a real-time clock. These devices were placed at approximately a half-extension of the road elements used for the validation. The presence of the traffic counters was disguised to avoid biasing driver behavior.

The vehicles used for the free-flow speed estimation in the real environment presented headways equal to or greater than 10 s to ensure free-flow travel conditions.

APPLICATION PERFORMED

Variable Estimation

The experimental study was performed in the DriS, and the variables were obtained for each driver. In Tables 3 and 4, the average variable values for the entire set of drivers are presented for each road and cross-section under consideration. As expected, higher speeds were practiced on the road with a less demanding horizontal alignment.

TABLE 3 Mean values collected for N 105-2

Scenario	1	2	3	4	5	6	7	8
Lane width (m)	3	3	3.3	3.3	3.6	3.6	3	2.7
Shoulder width (m)	0.8	1.2	0.8	0.3	0.8	0.3	0.3	0.8
Platform width (m)	2 × 3.8	2 × 4.2	2 × 4.1	2 × 3.6	2 × 4.4	2 × 3.9	2 × 3.3	2 × 3.5
Average travel speed (km/h)	67.4	71.1	72.9	73.8	71.3	76.0	73.9	73.6
Number of errors								
Centerline	7	6	5	5	3	3	5	7
Sideline	10	11	13	13	3	3	1	0
Total	17	17	18	17	6	6	6	7
% errors								
Centerline	6.7	5.3	4.44	4.7	1.7	1.8	5.1	6.0
Sideline	13.1	12.7	18.9	19.0	2.1	2.6	0.4	0.0
Total	19.8	18.0	23.3	23.6	3.7	4.4	5.4	6.0
Average distance (m)								
Centerline	0.6	0.63	0.71	0.70	0.83	0.83	0.58	0.48
Sideline	0.49	0.46	0.38	0.38	0.86	0.85	1.10	1.20

Scenario	9	10	11	12	13	14	15	16
Lane width (m)	2.7	2.7	3	2.7	3.3	3.6	3.3	3.6
Shoulder width (m)	0.3	1.2	1.8	1.8	1.2	1.8	1.8	1.2
Platform width (m)	2 × 3	2 × 3.9	2 × 4.8	2 × 4.5	2 × 4.5	2 × 5.4	2 × 5.1	2 × 4.8
Average travel speed (km/h)	71.3	74.5	77.6	76.8	75.8	79.8	79.4	79.0
Number of errors								
Centerline	5	6	3	5	2	1	2	1
Sideline	10	12	19	13	5	8	5	8
Total	15	18	22	19	7	9	7	9
% errors								
Centerline	5.4	4.5	2.4	4.2	1.4	1.2	1.8	1.3
Sideline	10.6	13.7	29.2	13.6	4.5	10.6	6.0	9.9
Total	16.1	18.2	31.6	17.7	5.9	11.8	7.8	11.2
Average distance (m)								
Centerline	0.47	0.49	0.63	0.50	0.77	0.89	0.77	0.88
Sideline	0.32	0.30	0.16	0.29	0.61	0.50	0.62	0.51

TABLE 4 Mean Values Collected for N 222

Scenario	1	2	3	4	5	6	7	8
Lane width (m)	3	3	3.3	3.3	3.6	3.6	3	2.7
Shoulder width (m)	1.8	2.2	1.8	1.2	1.8	1.2	1.2	1.8
Platform width (m)	2 × 4.8	2 × 5.2	2 × 5.1	2 × 4.5	2 × 5.4	2 × 4.8	2 × 4.2	2 × 4.5
Average travel speed (km/h)	106.4	118.3	121.7	123.2	105.80	116.4	115.9	116.2
Number of errors								
Centerline	1	1	1	1	1	1	1	2
Sideline	4	2	6	4	1	1	0	0
Total	5	3	7	5	2	2	1	2
% errors								
Centerline	1.3	1.8	1.5	1.7	1.0	0.8	1.2	3.7
Sideline	7.4	6.1	18.2	15.6	2.1	3.0	0.9	0.0
Total	8.7	8.0	19.7	17.4	3.1	3.9	2.0	3.7
Average distance (m)								
Centerline	0.62	0.61	0.75	0.72	0.90	0.89	0.65	0.50
Sideline	0.45	0.46	0.31	0.35	0.79	0.79	1.04	1.19

Scenario	9	10	11	12	13	14	15	16
Lane width (m)	2.7	2.7	3	2.7	3.3	3.6	3.3	3.6
Shoulder width (m)	1.2	2.2	2.5	2.5	2.2	2.5	2.5	2.2
Platform width (m)	2 × 3.9	2 × 4.9	2 × 5.5	2 × 5.2	2 × 5.5	2 × 6.1	2 × 5.8	2 × 5.8
Average travel speed (km/h)	96.4	111.0	113.1	116.1	95.9	111.4	113.6	116.5
Number of errors								
Centerline	3	3	1	4	1	1	1	1
Sideline	6	6	8	5	2	4	2	4
Total	9	8	10	8	3	5	3	5
% errors								
Centerline	4.2	5.1	2.8	5.5	1.8	1.2	1.5	1.6
Sideline	15.6	14.8	28.9	14.7	7.2	13.4	3.3	11.5
Total	19.9	19.9	31.8	20.2	9.0	14.7	4. 9	13.1
Average distance (m)								
Centerline	0.47	0.47	0.60	0.46	0.75	0.88	0.71	0.82
Sideline	0.29	0.30	0.16	0.30	0.62	0.48	0.65	0.54

Vehicle Positioning in Cross-Section

In Figure 2, the variation in the average distance to the sideline with the cross-section width is presented. The reference values for the distance to sideline, established for a vehicle traveling at the center of the lane, are represented by the dashed line.

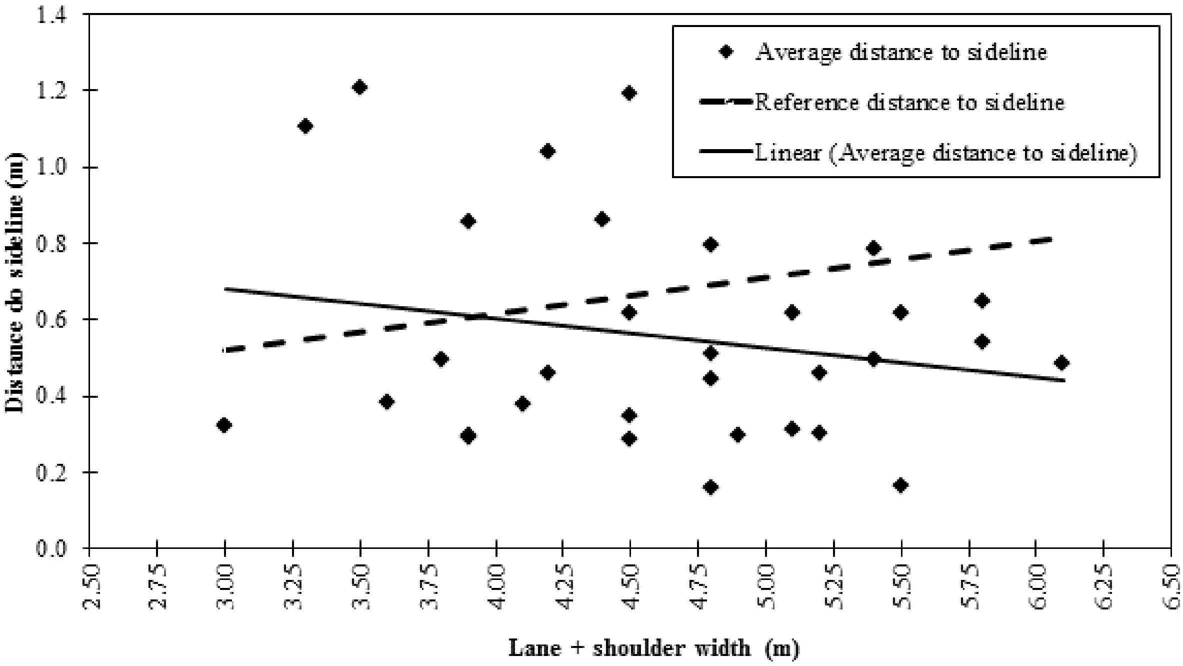

FIGURE 2 Average distance to sideline for different platform widths.

For large cross-section widths, drivers tended to travel closer to the sideline because of higher horizontal clearances caused by the increase in shoulder width. As the lane and shoulder width decreased, drivers tended to move toward the centerline to attempt to maintain the same speed, holding the distance to the objects on the roadside. As a consequence of the smaller distance to the opposing traffic stream, drivers tended to reduce speed in the presence of oncoming vehicles.

Multivariate Analysis

To evaluate the effects of the lane and shoulder widths of both road types on the free-flow speed, a multivariate linear regression using Equation 2 was performed with the data collected in the simulated environment. The model was conducted using the statistical software for econometric analysis Limdep (*8*). The regression coefficients and corresponding *P*-values for the set of considered variables are presented in Table 5.

The majority of the considered variables are statistically significant at a 10% level. The exceptions were Driver 1 and 4 dummy variables. However, the corresponding coefficients were nearly zero, revealing that the behavior of these drivers was similar to that of the base driver.

The speed practiced by the most aggressive driver was around 30% higher than the speed adopted by the least aggressive driver.

The goodness of fit was evaluated with the correlation coefficient (R = 0.89). According to Cohen (*9*), a coefficient value above 0.5 represents large correlations between the variables. The coefficient of determination (R^2) expresses that 79% of free-flow speed variance is explained by the variance of the independent variables.

TABLE 5 Coefficients of Multiple Linear Regression

Variable	Coefficient	P-value
Constant	4.455	0.000
Cross-section:		
Lane width: l	0.143	0.006
Shoulder width: s	0.171	0.050
Lane width × Shoulder width: ls	-0.128	0.093
Dummy variables:		
Road type: d_r	0.385	0.000
Driver 1: d_{d1}	-0.038	0.182
Driver 2: d_{d2}	-0.081	0.005
Driver 3: d_{d3}	-0.049	0.090
Driver 4: d_{d4}	0.002	0.934
Driver 5: d_{d5}	-0.349	0.000
Driver 6: d_{d6}	-0.159	0.000
Driver 7: d_{d7}	-0.159	0.000
Driver 8: d_{d8}	-0.119	0.000
Driver 9: d_{d9}	-0.075	0.009
Driver 10: d_{d10}	-0.133	0.000
Driver 11: d_{d11}	-0.091	0.002
Driver 12: d_{d12}	-0.135	0.000
Driver 13: d_{d13}	-0.086	0.003
Driver 14: d_{d14}	-0.122	0.000
R=0.89		
R^2=0.79		

Note: d_{di} expresses the behavior of driver i when compared with the base driver.

For the road with the lower design speed ($d_r = 0$), the free-flow speed was obtained for each cross-section by averaging the free-flow speed practiced by the 15 drivers. The same procedure was adopted for the road with the higher design speed ($d_r = 1$).

The Kolmogorov-Smirnov test was performed for the 32 samples of the 15 speed values obtained in each cross-section. Each sample was accepted as being normally distributed for a significance level of 5%, ensuring that the average speed value was representative of the sample.

The elasticities at the sample mean were 0.12% for lane width and 0.025% for shoulder width. These values represent the increase in free-flow speed caused by a 1% increase in lane or shoulder width. However, it is more important to observe the variations in speed produced by different combinations of lane and shoulder widths than to analyze the effects at the sample mean. Thus, Equation 2 was applied to diverse combinations of cross-sections. The speed reduction results are presented in Table 6.

TABLE 6 Reduction in Free-Flow Speed (km/h) According to Lane and Shoulder Widths

Lane Width (m)	Shoulder Width (m)								
	N 105-2				N 222				
	0.3	0.8	1.2	1.8	0.3	0.8	1.2	1.8	2.2
2.7	6.8	3.7	2.3	1.0	9.9	5.4	3.4	1.5	0.5
3.0	4.6	2.3	1.4	n/a	6.7	3.4	2.1	0.7	n/a
3.3	2.5	1.1	0.6	n/a	3.7	1.7	0.8	n/a	n/a
3.6	0.6	0.0	n/a	n/a	0.9	0.0	n/a	n/a	n/a

Some observations arise from a comparison of Table 1 and Table 6. First, the baseline scenario, corresponding to the minimum cross-section, above which significant variations on free-flow speed (<0.5 km/h) are no longer observed, is established in this study for a lane 3.6 m wide combined with a shoulder 0.8 m wide. These baseline widths are valid for both of the studied road types. For wider cross-sections, the free-flow speed was strongly influenced by geometric characteristics other than lane and shoulder widths. The base cross-section proposed by the HCM (*1*) is formed by a lane 3.6 m wide and a shoulder 1.8 m wide. Because this reference manual was developed for North American conditions, where vehicles are generally wider than in Europe, the minimum cross-section not influencing the free-flow speed was expected to be smaller in Portugal.

It is also possible to confirm that narrower cross-sections produce greater effects on the free-flow speed. These effects were gradually reduced with increases in lane and shoulder widths. This study obtained values of speed reduction that were different from those of the HCM (*1*). The speed reductions proposed in Table 1 for narrower cross-sections are proportional to those found in Table 6 for the less demanding road (N 222). Moreover, despite the differences in the baseline scenario between this study and the HCM (*1*), the speed reduction for the narrowest cross-section observed at N 222 was close to the value proposed by the HCM (*1*): approximately 10 km/h.

The geometric characteristics of the road with a lower design speed (N 105-2) were significantly different from the characteristics of the roads considered by the HCM (*1*). The HCM considers two-lane highways with operating speeds between 70 and 110 km/h. However, the comparison of the two roads shows that the effects of the width of the cross-section on the free-flow speed depend on the range of speed. The average travel speed observed in the DriS for N 105-2 was approximately 68% of the speed for N 222. This proportion is approximately the same observed for the speed reductions between both roads for each lane and shoulder width combination.

Another important conclusion from Table 6 is that the effects caused by variations in lane and shoulder widths were not cumulative: the speed reduction for a combined lane and shoulder decrease was higher than the sum of the speed reductions caused by the correspondent decreases in lane and shoulder widths individually. Marginal effects of lane and shoulder width on speed may be obtained through deriving the regression function (Equation 2) with respect to the shoulder [ln (s)] or lane [ln (l)] widths.

For example, in Table 6, it is possible to observe that the reduction in shoulder width from 0.8 m to 0.3 m varies according to the lane width. Likewise, the decrease in lane width from 3.6 m to 2.7 m depends on the shoulder's variation.

Conversely, the HCM (*1*) does not reflect different reductions in the free-flow speed from a combined lane and shoulder decrease or the sum of the correspondent individual effects (i.e., the speed reductions between two successive intervals of lane width presented in Table 1 are independent of shoulder width and vice versa).

Spot Speed Comparison between Simulated and Real Environments

To validate the results from the driving simulator, a comparative analysis of spot speeds measured in the simulated and real environments was performed. For each of the six points of control, the average spot speeds in the real environment (SS_r) and the simulated environment (SS_s), the corresponding difference ($SS_s - SS_r$), and the standard deviations (SD_r and SD_s) were evaluated. The sample size in the real environment (N_r) depended on the traffic passing at each point of control. In the simulated environment, the sample size (N_s) was formed by the 15 drivers of the DriS.

Table 7 presents the variables used for comparing the spot speeds between the real and simulated environments. The radii and extensions of the road sections containing the points of control are also presented.

TABLE 7 Spot Speed Comparison of Real and Simulated Environments

Point of Control (R; Ext.) (m)	SS_r (km/h)	SD_r (km/h)	SS_s (km/h)	SD_s (km/h)	N_r	N_s	SS_s - SS_r (km/h)
N 105-2							
I (∞; 334)	54.2	16.1	92.7	16.3	164	15	38.7
II (150; 80)	46.8	13.2	77.1	9.9	133	15	30.3
III (∞; 473)	76.3	18.6	98.6	11.2	112	15	23.6
N 222							
I (545; 282)	71.5	16.3	113.7	17.6	323	15	42.2
II (∞; 240)	76.9	16.8	119.4	20.3	325	15	42.4
III (∞; 408)	76.6	13.7	115.7	19.7	330	15	38.7

Despite the sample size differences between the real and simulated environments, the statistical dispersion observed for SS_r and SS_s is reasonably similar. On N 222, where characteristics other than geometry can produce higher effects on traffic flow, speed dispersion was smaller for the real environment. On N 105-2, where drivers are strongly conditioned by the geometry of the horizontal alignment, the differences in speed dispersion tended to be smaller.

For each point of control, the samples obtained in both the real and simulated environments were considered as normally distributed samples for a significance level of 5% through the Kolmogorov-Smirnov test, revealing similarities in drivers' behavior.

Table 7 shows that ordering the points of control of each road by speed results in the same sequence for both environments. Drivers tended to adopt higher speeds in the simulated environment than in the real environment. However, this result seems to reflect a translation of the absolute speed values that does not affect the conclusions of this study. Therefore, the results obtained with the DriS were considered to be valid, both in terms of relative and absolute speed differences.

Higher speeds were expected in the simulated environment because of the lack of grip effects and dynamic behavior of the car body. On N 222, the speed difference between both environments was approximately 40 km/h. On N 105-2, this value was reduced to approximately 30 km/h because of the constraints imposed on drivers by the more demanding road alignment.

CONCLUSIONS

Previous studies have suggested that the width of road cross-sections affect the free-flow speed chosen by drivers. The HCM (*1*) and the corresponding background study [NCHRP Project 3-55(3)] (*2*) take those effects into account by proposing values for speed reductions caused by different lane and shoulder widths. This study also confirmed the effects of the road cross-section on the free-flow speed; this confirmation is emphasized by the significance of lane and shoulder width revealed in the multivariate analysis.

However, the obtained results differ from the HCM (*1*) proposals on three main points. The base cross-section, defined as the minimum combination of lane and shoulder widths above which a decrease in the free-flow speed is no longer observed, is formed by a lane 3.6 m wide and a shoulder 0.8 m wide instead of a lane 3.6 m wide and a shoulder 1.8 m wide, as proposed by the HCM (*1*). Consequently, the speed reductions determined for smaller cross-sections also differed from the HCM (*1*). However, the obtained speed reduction for the narrowest cross-section (a lane of 2.7 m and shoulder of 0.3 m) was approximately 10 km/h, which is close to the same value as that proposed by the HCM (*1*). Finally, an interaction between the effects of lane and shoulder width on free-flow speed was revealed, and they are not cumulative. Therefore, a simultaneous decrease in lane and shoulder widths produces a greater reduction in the free-flow speed than the sum of the same effects taken individually. This conclusion may contribute to a review of the lack of evidence assumed in the NCHRP Project 3-55(3) (*2*) for the existence of such interaction.

Despite being a widely adopted reference manual, the HCM (*1*) was developed for North American conditions, and its applicability to road networks with different geometric and environmental characteristics (e.g., roads in Portugal or other European countries) should be carefully considered.

From a comparison of the two considered roads, it is possible to conclude that the influence of a cross-section on the free-flow speed also depends on the order of magnitude of the driving speeds.

The validity of the results obtained in the simulated environment confirms that driving simulators are reliable and flexible tools that may be used to create and study realistic traffic situations.

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FREE-FLOW SPEED MODEL BASED ON PORTUGUESE ROADWAY DESIGN FEATURES FOR TWO-LANE HIGHWAYS

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FREE-FLOW SPEED MODEL BASED ON PORTUGUESE ROADWAY DESIGN FEATURES FOR TWO-LANE HIGHWAYS

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ABSTRACT

Speed is a key performance measure in economic and environmental analyses of two-lane highways. Speed, combined with the percentage of time spent following, is also used in the assessment of level of service. Under free-flow conditions, the circulation of a given vehicle is not constrained by the presence of other vehicles, and the driver’s speed choice reflects the driver’s response to the geometric features of the road and roadside interference, as well as the driver's perception of risk. Many studies concerned with the effects of road characteristics, design features in particular, on vehicle speed have been conducted in several countries in recent decades. These studies have provided useful tools for modeling speed and evaluating alignment consistency. This paper presents an exponential free-flow speed model, applicable to both curves and tangents, developed for two-lane highways in Portugal. The variables included in the model are representative not only of the road element under consideration (curve or tangent) but also of the preceding road section and of the visual field downstream from the element. The results from this model are compared with other authors’ results and with the guidelines in the Highway Capacity Manual 2010. In addition to the primary influence of the horizontal curvature on speed, the results show that other factors, such as the cross-sectional width, the density of access points, and the downstream visibility, are important.

INTRODUCTION

Speed is a major factor in the assessment of road performance. Depending on the functional classification of a given road, a design speed is established, and engineers define the geometric features of the road to ensure that drivers can, in normal traffic conditions, achieve the expected average travel speed to reach their destinations on time. Furthermore, an operating speed may be estimated for performance evaluation during the road operation period. Real environment speed measurements are required, and the operating speed is typically associated with the 85th percentile of the observed speed distribution (*1*). Speed is usually recognized by road planners, designers, and users as an important measure for the evaluation of the level of service, speed limit definition, design consistency and safety analyses, and other essential studies.

Recognizing the role of speed in road performance evaluation, the Highway Capacity Manual (HCM) 2010 (*2*) recommends speed as the most appropriate concept for use in the economic and environmental analyses of two-lane highways, including the assessment of the impact on air quality and noise level. In addition, the HCM methodology to assess the level of service of this type of road also uses the average travel speed as an input, which in turn depends on the free-flow speed (FFS) and on the traffic volume. In other words, the average travel speed adds the effects of the delays caused by the remaining traffic to the FFS. The FFS reflects the drivers' response to the road's geometric and environmental features because drivers are not affected by the presence of other vehicles. The definition of the FFS proposed by the HCM is similar to the definition of operating speed given by the AASHTO *Green Book* (*1*). However, operating speed may also be affected by drivers' perception of risk, speed limit and enforcement, general driving practices and culture, and vehicle technology. For this reason, speed prediction models have been developed in different regions worldwide and in different time periods.

Reference manuals and national guides for road design usually define operating speed for a road section rather than for specific design elements. The HCM (*2*) establishes a base FFS as the speed observed for roads presenting no access points and lane and shoulder widths equal to or greater than 3.6 m and 1.8 m, respectively. The HCM also provides an FFS estimation model, taking into account speed reductions to the base FFS caused by smaller cross-sections and higher densities of access points.

The AASHTO *Green Book* (*1*) also provides some recommendations for design and operating speeds. Different design speeds are suggested according to the functional classification intended for a planned road, and speed differences between adjacent road sections are recommended to avoid excessive values of acceleration or deceleration. In brief, the guidelines for road design proposed by this manual consist of an effort to provide efficient infrastructures, capable of dealing with the expected operating speeds and travel times and of ensuring the required safety standards along the road's entire length.

Similar criteria are proposed by the Portuguese guidelines for road design (*3*). In other countries, official approaches suggest operating speeds based on the curvature change rate and pavement width, in the case of Germany (*4*), and on the amount of bend or curvature and mean visibility, in the case of the United Kingdom (*5*).

Many authors have also been working on modeling speed using an academic approach. A microscopic perspective has been commonly adopted by the researchers who have been exploring a comprehensive range of factors with potential impacts on speed, resulting in several speed models for different geometric features, types of vehicles, and environmental conditions. Some useful tools for a thorough design consistency evaluation have been provided by these studies (*6–9*).

The horizontal alignment has usually been regarded as the most important factor affecting speed, and its curvature may be characterized by different indicators, such as the radius, the degree of curve, the curvature change rate, and the deflection angle. Several models consider these features as the only ones exerting significant impacts on speed, such as the work by Morrall and Talarico (*10*), Passetti and Fambro (*11*), Misaghi and Hassan (*12*), and Kanellaidis et al. (*13*).

The influence of the vertical alignment on speed has been less studied than the effects of the horizontal alignment, perhaps because of its smaller importance to the circulation of passenger cars. Nevertheless, some relevant research on this field has been conducted to account for the simultaneous effect of the horizontal and vertical alignments on driving behavior. The research conducted by Fitzpatrick et al. (*14*) and Gibreel et al. (*15*) proposed speed models categorized by vertical alignment conditions. Donnell et al. (*16*) modeled the speed of trucks in horizontal curves; they took into account the grades of the approach and departure tangents.

The effects of the cross-sectional width have also been studied by several authors. Lamm and Choueiri (*7*) used the lane and shoulder widths as inputs for a speed model developed for the state of New York, Lamm et al. (*8*) proposed speed models categorized by lane widths. Melo et al. (*17*) conducted a driving simulator study to estimate speed reductions produced by different lane and shoulder widths; they compared the results with the HCM guidelines (*2*).

The influence of the driver's expectations about the road alignment has been introduced in spot speed models through the use of variables to characterize the upstream and downstream road sections. In this sense, the speed on the approach tangent, used by Krammes et al. (*6*) and Bonneson et al. (*18*), and the concept of desired speed of the road section proposed by McLean (*19*) were included in the curve speed models developed by these authors. The downstream features considered in the literature are mainly related to the driver's field of vision (*5*, *20*).

Other variables have been considered in speed modeling, such as the curve or tangent extension (*6*, *21–23*), the superelevation rate (*15*, *18*, *21*), and the posted speed limit (*8*, *22*).

Although numerous speed models have been proposed by the research community, public authorities, and road operators, the model presented in this paper is distinctive in two ways: (a) it allows for the FFS estimation for a given curve or tangent, taking into account not only the characteristics of the element but also the effects of upstream and downstream road sections, and (b) it uses an exponential regression approach for the FFS modeling instead of the commonly used linear form. These two features address concerns raised in the *Transportation Research Circular E-C151* (*24*), namely the relatively few tangent speed models and the limitations of linear regression.

The proposed FFS model is applied to Portuguese two-lane highways, and because it can be applied to curves and tangents, it may also be used as a design consistency evaluation tool, providing an alternative to the procedure in the Portuguese guide for road design (*3*).

DESCRIPTION OF THE MODEL

The model estimates the FFS at a given horizontal element of the road (curve or tangent) through an exponential function of the road features, as shown in Equation 1:

$$FFS = f\left(X_{ele,} X_{up}, X_{down}\right) = \beta_0 \cdot \exp\left(\beta_1 X_{ele}\right) \cdot \exp\left(\beta_2 X_{up}\right) \cdot \exp\left(\beta_3 X_{down}\right) \qquad (1)$$

where

X_{ele} = features of the road element,
X_{up} = features of the upstream road section,
X_{down} = features of the downstream road section, and
β_0, β_1, β_2, β_3 = regression coefficients.

An advantage of the exponential equation is the interaction between the effects of road features and the order of magnitude of the practiced speeds. In the linear form of the FFS calculation, however, independent variables produce cumulative impacts on speed that are independent from the road type. Thus, the adoption of an exponential function seems to be more appropriate for speed modeling for European countries, where operating speeds on two-lane highways differ significantly, resulting in changing the effects of road geometrics.

The three sets of variables X_{ele}, X_{up}, and X_{down} represent the road geometric features and roadside interference that impact drivers' speed choice. X_{ele} characterizes the curve or tangent in which the FFS is being estimated and may encompass factors such as the horizontal radius, length, grade, lane width, and shoulder width. X_{up} describes the upstream road section that may affect the FFS and includes factors such as the density of intersections and roadside buildings. The upstream road section to be considered may vary in length depending on the local conditions. X_{down} represents the downstream road features that may affect driving behavior and is typically influenced by the sight distance. In summary, the model proposed in Equation 1 expresses the idea that a driver's behavior on a given tangent or curve depends not only on the characteristics of that element but also on the recent driving experience and on the road features that the driver can observe downstream. This assumption has been explored by other authors, although they have used different approaches.

APPLICATION OF THE MODEL

Data Description

In the test of the FFS model on Portuguese roadways, the case study road sections were chosen from five roads in northern Portugal: N 14, N 101, N105-2, N 206, and N 222. These road sections are located outside the urban areas, and the marginal land use varies from the complete absence of construction to the existence of some isolated buildings, as shown in Figure 1. The posted speed limits are of 50, 70, or 90 km/h, and the terrain type is consistent with the classification of rolling terrain (*2*).

Spot speed data were collected from 61 curves and 27 tangents over the 116 km of road. Because the model uses both upstream and downstream road features, speed must be measured separately for each direction, doubling the number of observations (176 observations).

Speed measurements were performed during the day in clear weather conditions. The pavement of the selected sections was in good shape, without cracks or potholes (which may cause speed reductions) and with clearly visible markings. Vehicle speeds were recorded with traffic counting devices, a Doppler radar sensor with an integrated Flash RAM data memory, and a real-time clock, which were placed at the approximate midpoint of the selected tangents and curves. Because drivers tend to brake in the presence of unfamiliar objects installed at the roadside, when possible, the equipment was fixed at a height of approximately 2.5 m using public lighting poles. When this installation was not possible, other steps were taken to disguise the traffic counters.

FIGURE 1 Examples of road sections considered for case studies.

The FFS associated with a particular road element is the 85th percentile of the speed distribution of unconstrained vehicles (*V85*). It is assumed that free-flow traveling is established between vehicles that are separated by at least 6 s, as proposed by Lobo et al. (*25*) in a study conducted on Portuguese two-lane highways. The spot speeds of more than 90,000 free-flow vehicles were measured at the selected sites, ensuring a minimum of 100 registers per direction for each site, as recommended by the HCM for *V85* estimation (*2*). The percentage of heavy vehicles traveling in the case study roads is estimated in around 10% of the total number of vehicles.

The road geometry and roadside interference data were collected with an onboard GPS device and a digital video recording system installed in the instrumented vehicle of the Traffic Analysis Laboratory of the Faculty of Engineering of the University of Porto. Besides the vehicle speeds, the collected variables were the following:

- Features of the road horizontal element (i.e., dummy variable for curves, curve radius, length, grade, one-direction pavement width, and extra lateral clearance);
- Features of the upstream road section (i.e., amount of bend or curvature, density of intersections, and density of roadside buildings);
- Feature of the downstream road section (i.e., dummy variable for constrained visibility).

In the FFS model, to account for curves or tangents using the same mathematical expression, the dummy variable for curves is set to 1 for a curved section and to 0 for a tangent section. The curve radius is eliminated for the tangent section by multiplication by the dummy variable. Representative average values for the sites were used for the grade and the cross-sectional variables. The pavement width (in one-direction) is given by the sum of the lane and shoulder widths, and the extra lateral clearance is the distance between the shoulder external limit and any fixed object at the roadside.

In the Portuguese case study, the FFS for a given curve or tangent includes effects from the 1-km-long upstream road section. The amount of bend or curvature is represented by the total deflection angle of the horizontal alignment per kilometer, and the densities of roadside buildings and intersections correspond to the number of marginal constructions per kilometer and the number of intersections with other public roads per kilometer, respectively. Because reliable vertical alignment data could not be collected through the GPS data collection system, this feature was not included. The authors believe that the upstream vertical alignment does not affect the FFS significantly, as compared with the upstream horizontal alignment, which influences drivers' expectations of the road's safety standards.

A single dummy variable representing the driver's visibility is used to characterize the effects of the downstream road section on the FFS. This variable implies that the downstream section affects the driver's choice of speed only through the geometric features that the driver is able to see at the moment. The dummy variable is equal to 1 if the driver is driving on a curve with a radius equal to or smaller than the absolute minimum radius or if there is such a curve within the decision sight distance; the variable is equal to 0 otherwise. The absolute minimum radius and the decision sight distance depend on the operating speed and are defined in the Portuguese guide for road design (*3*).

The statistics of the variables included in the model for the test sites are shown in Table 1.

TABLE 1 General Data on Curves and Tangents

Variable Description	Average	Standard Deviation	Minimum	Maximum	Relative Frequency (%)
Curves – 122 observations					
Free-flow speed (km/h)	65.2	12.1	43.0	98.0	n/a
Element features					n/a
Curve radius (m)	181.4	156.6	35.0	680.0	n/a
Length (m)	116.4	71.8	40.3	387.3	n/a
One-direction pavement width (m)	5.5	1.6	3.4	16.3 [a]	n/a
Extra lateral clearance (m)	0.4	0.6	0.0	3.0	n/a
Upstream features					n/a
Bendiness (degrees/km)	239.7	172.4	13.8	854.7	n/a
Density of intersections (no./km)	3.4	2.0	0.0	10.0	n/a
Downstream feature					
Dummy for constrained visibility	n/a	n/a	n/a	n/a	52.5
Tangents – 54 observations					
Free-flow speed (km/h)	73.7	9.4	59.0	94.0	n/a
Element features					n/a
Length (m)	344.7	200.5	161.0	1,054.9	n/a
One-direction pavement width (m)	4.9	1.4	3.1	9.6	n/a
Extra lateral clearance (m)	0.3	0.5	0.0	1.7	n/a
Upstream features					n/a
Bendiness (degrees/km)	182.9	140.0	8.9	593.5	n/a
Density of intersections (no./km)	3.5	2.1	0.0	9.0	n/a
Downstream feature					
Dummy for constrained visibility	n/a	n/a	n/a	n/a	20.4

[a] This exceptional value corresponds to one site featuring an unmarked parking area at the roadside.

Regression Modeling

A multiple exponential regression using a linearized form of Equation 1 was used to model the FFS for Portuguese two-lane highways. The regression coefficients and standard errors are shown in Table 2. With the exception of the dummy variables, these coefficients represent the elasticities of the road features.

TABLE 2 Results of Multiple Exponential Regression

Variable	Coefficient	Standard Error
Constant	3.999	0.132 [a]
Element features		
Dummy for curve	-0.626	0.093 [a]
Curve radius	0.118	0.017 [a]
Length	0.065	0.019 [a]
One-direction pavement width	0.058	0.035 [b]
Extra lateral clearance	0.009	0.004 [a]
Upstream features		
Bendiness	-0.019	0.011 [b]
Density of intersections	-0.036	0.014 [a]
Downstream feature		
Dummy for constrained visibility	-0.043	0.023 [b]
Residuals		
Sum of squares = 1.96		
Standard error = 0.11		
Fit		
R = 0.81		
Adjusted R^2 = 0.63		
Log-likelihood = 145.95		
Autocorrelation		
Durbin-Watson statistic = 1.29		
Rho = 0.36		

[a] Significant at the 5% level.
[b] Significant at the 10% level.

The correlation coefficient (R) above 0.50 achieved by the exponential model represents large correlations between the dependent and the independent variables (*26*). For comparison, a linear regression was also applied to the data, resulting in a lower coefficient of determination (R^2). The residuals are normally distributed, as confirmed by the Kolmogorov-Smirnov test, resulting in a p-value of 0.49.

The results presented in Table 2 show that traveling in a curved section is the most important factor that affects speed choice, and the factor may negatively impact the FFS about 47%. Such behavior was expected because curves with relatively large radii are uncommon in Portuguese two-lane highways, and the test case road sections are not exceptions. The decrease in 10% of the curve radius produces a FFS reduction of about 1.2%. The length of the element presents a positive elasticity (0.065), which is similar to the combined effects of the cross-section variables (0.067).

Harsher geometric features and roadside interference of the adjacent sections reduce the FFS at a given curve or tangent, although they produce smaller effects than the specific conditions at the road element. The increase in 10% of both upstream features – amount of bend or curvature and density of intersections – causes a decrease in the FFS of about 0.6%, and the downstream constrained visibility may reduce the FFS in around 4%.

Two of the collected variables, grade and density of roadside buildings, were not statistically significant at the 10% level and were subsequently removed from the model. In this case study, the density of roadside buildings shows multicollinearity with the density of intersections because the increase in the number of access points is highly correlated with the crossing of small villages. The lack of significance of the grade may be related to the relatively small grades observed at the speed test sites, with absolute values rarely exceeding 5% and with an average value of 3%. Therefore, the proposed FFS model is not recommended for mountainous terrain conditions.

The FFS model proposed for Portuguese two-lane highways is shown in Equation 2:

$$\begin{aligned} FFS = \exp[&3.999 - 0.626C + 0.118\ln(R)\cdot C + 0.065\ln(L) + 0.058\ln(PW) + \\ &+ 0.009\ln(ELC) - 0.019\ln(B) - 0.036\ln(DI) - 0.043CV] \end{aligned} \tag{2}$$

where

FFS = free-flow speed (km/h),
C = dummy variable for curve,
R = curve radius (m),
L = length (m),
PW = one-direction pavement width (m),
ELC = extra lateral clearance (m),
B = bendiness (amount of bend or curvature) (degrees/km),
DI = density of intersections (number per km), and
CV = dummy variable for constrained visibility,

and

ELC, B, DI > 0.

COMPARISON WITH EXISTING SPEED MODELS

In this section, the results of the proposed FFS model are compared with other speed models proposed by different authors, as well as with the HCM methodology for FFS estimation on two-lane highways (*2*).

The horizontal design features are recognized as the main factors affecting the operating speed, and their effects have been widely studied and reported in the literature. Therefore, the influence of the curve radius on the FFS is, among the variables included in this study, the most reliable term of comparison with the existing speed models.

Because these models usually represent linear functions of the radius (*R*), curvature (*1/R*), degree of curve (*DC*), or other related variables, direct comparisons between coefficients and elasticities are not possible. Thus, the radius elasticities were estimated for a set of selected models. First, the models from the literature were applied to the case study to estimate the FFS for the sample mean. Then, the radius elasticity was calculated by evaluating the impact on the FFS of a 100% increase in its mean value, with the other variables remaining constant. The results are presented in Table 3.

The radius elasticity of 0.118 obtained for Portuguese conditions is aligned with other model results, and the relatively small differences between these figures may be related to the specific local conditions and driving culture of each region.

TABLE 3 Evaluation of Radius Elasticity for Existing Speed Models

Authors	Location	Speed Model [a]	Radius Elasticity
Morrall and Talarico (*10*)	Alberta, Canada	$V85 = \exp(4.561 - 0.00586DC)$	0.094
Passetti and Fambro (*11*)	New York, Pennsylvania, Oregon, Washington, Minnesota, and Texas, USA	$V85 = 103.9 - 3020.5/R$	0.102
Misaghi and Hassan (*12*)	Ontario, Canada	$V85 = 91.85 + 0.00981R$	0.022
Kanellaidis et al. (*13*)	Greece	$V85 = 129.88 - 623.1/\sqrt{R}$	0.165

[a] where $V85$ = free-flow speed (km/h), and DC = degree of curve (degrees/100 m of arc) = $5729.58/R$.

From another perspective, the HCM (*2*) proposes the following FFS estimation model:

$$FFS = BFFS - f_{LS} - f_A \tag{3}$$

where

$BFFS$ = base free-flow speed (km/h),
f_{LS} = adjustment parameter for lane and shoulder width (km/h), and
f_A = adjustment parameter for density of access points (km/h).

It is recommended that Equation 3 be used to estimate the FFS when speed measurements are not possible. In the HCM model, two correction values, f_A and f_{LS}, representing road geometric features, are applied to a BFFS, which is the speed observed for roads with (a) no access points and (b) lane and shoulder widths equal to or greater than 3.6 m and 1.8 m, respectively. The correction values result in reductions to the FFS because of higher densities of access points and smaller cross-section widths.

The HCM methodology is applicable to road sections instead of specific design features (tangents or curves), as is the case of the model presented in this paper. However, because the latter model also encompasses the effects of access point density and of cross-section width, only the sites collected in tangent were considered for the comparison with the HCM model. Otherwise, the results could be strongly affected by the local horizontal curvature. Speed reductions for the same categories of access point density used in the HCM were estimated through the proposed FFS model, using the base cross-section width of a 3.6-m-wide lane combined with a 1.8-m-wide shoulder and the sample mean values of the remaining variables. Similarly, speed reductions for the same cross-section features considered in the HCM were evaluated through the proposed FFS model with no access points and the sample mean values of the remaining variables. The results are presented in Table 4 (f_A) and in Table 5 (f_{LS}).

TABLE 4 Reduction in FFS from Access Point Density (km/h)

Access Points per km	HCM 2010	Proposed Model
0	0.0	0.0
6	4.0	4.9
13	8.0	6.9
19	12.0	7.9
25	16.0	8.6

TABLE 5 Reduction in FFS from Cross-Section Width (km/h)

HCM 2010					Proposed Model				
Lane	Shoulder Width (m)				Lane	Shoulder Width (m)			
Width (m)	≥0.0<0.6	≥0.6<1.2	≥1.2<1.8	≥1.8	Width (m)	0.0	0.6	1.2	1.8
2.7<3.0	10.3	7.7	5.6	3.5	2.7	3.1	2.2	1.5	0.8
≥3.0<3.3	8.5	5.9	3.8	1.7	3.0	2.6	1.8	1.1	0.5
≥3.3<3.6	7.5	4.9	2.8	0.7	3.3	2.2	1.5	0.8	0.3
≥3.6	6.8	4.2	2.1	0.0	3.6	1.8	1.1	0.5	0.0

The proposed FFS model returns values for f_A that are similar to the results for the HCM model for the lower categories of access point density. However, unlike the linear behavior assumed by the HCM, estimated speed reductions tend to stabilize as the access point density increases.

With respect to the f_{LS} values, the results of the proposed FFS model differ significantly from those of the HCM model. First, the inclusion in the model of a wider range of geometric features affecting the FFS leads to an expected reduction in the individual effects of each independent variable. Second, because an exponential function was used, the effects of the road features on the FFS are not cumulative; they depend on the order of magnitude of the speeds practiced on the roads under consideration. In European countries such as Portugal, driving speeds may be considerably different from one road to another and lower than the speeds practiced on most North American two-lane highways. Thus, for the same cross-sectional characteristics, smaller values of f_{LS} may be observed in Europe.

CONCLUSIONS

Speed has been a major concern for researchers in road operations and design, and these researchers have developed numerous operating speed models that are applicable in different regions worldwide. This paper presents the development and testing of a new model to estimate FFS based on the relationship between speed and road geometric features for Portuguese two-lane highways, on which little research has been conducted.

The new model presents two main features that are unusual among the existing models: (a) it takes into account the effects on the FFS produced by the geometries of the sections upstream and downstream from the element under consideration and (b) it uses an exponential function that assumes that the magnitude of the geometric effects is dependent on the order of magnitude of the speeds practiced at a given location. Furthermore, as the model is applicable both to curves and tangents, it may constitute an alternative procedure for design consistency evaluation to that established by the Portuguese guidelines (*3*).

The results of the modeling application to the Portuguese case study confirmed the primary influence of the horizontal curvature on the operating speed, followed by the secondary influences of element extension and cross-sectional characteristics. The amount of bend or curvature and the roadside interference of the upstream section as well as the downstream constrained visibility also had a significant impact on the FFS, although smaller than the geometric effects of the element.

The influence on the FFS produced by some of the variables considered in this model may vary from the findings of other studies, especially those that were developed for different conditions of road design standards and driving culture, as is the case of the HCM (*2*). The authors recommend caution when applying the proposed model outside European. However, the development of new speed models for non-European conditions that present a similar structure to this model would likely improve speed prediction capabilities.

Additional research on FFS modeling for sections of Portuguese two-lane highways will be conducted in the future.

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ESTIMATING PERCENTILE SPEEDS FROM MAXIMUM OPERATING SPEED FRONTIER

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ESTIMATING PERCENTILE SPEEDS FROM MAXIMUM OPERATING SPEED FRONTIER

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ABSTRACT

Most operating speed studies have focused on modeling a specific percentile speed, most notably the 85th, as a function of the road geometrics. This method has resulted in some drawbacks, such as the loss of information due to speed data aggregation, the inability to capture speed dispersion, and few references about the effects of the driving culture and vehicle characteristics on the practiced speeds. Therefore, an operating speed frontier model to improve speed prediction capabilities, is presented. The deterministic component of the model represents the maximum operating spot speed as a function of the local geometric features, whereas the disturbance term includes the non-geometric effects, such as driving behavior, type of vehicle, and road environment. Data are collected in 88 curves and tangents of Portuguese two-lane highways located outside urban areas; approximately 18,000 free-flow vehicles were observed. Following an innovative approach to operating speed modeling, the model is estimated with a stochastic frontier regression between the speeds of all free-flow vehicles and the geometric features at the measurement sites. In addition to the maximum operating speed, the new model is capable of estimating any percentile speed through the cumulative function of the one-sided disturbance while avoiding speed data aggregation. Moreover, the road geometric features required to implement the model are easy to obtain either by consulting the design project or by preforming on-site measurements; this ability contributes to the model's applicability in different regions.

INTRODUCTION

Operating speed studies have gained relevance across the past decades since several countries started to consider the predicted driving speed as an input to the definition of roadway geometric standards in the guidelines for road design. In several studies the research community, public authorities, and road operators have developed the prediction of operating speed and evaluated the effects of different factors on the speed, such as road geometry and functional classification, roadside interference, traffic, speed limits, and weather conditions. These studies produced a large number of tools for speed modeling (*1, 2*) and design consistency evaluation (*3, 4*) that are used by practitioners worldwide.

The AASHTO *Green Book* recognizes the 85th percentile of the speed distribution as the most commonly used operating speed measure (*5*). However, in *Transportation Research Circular E-C151* (*1*), it is pointed out that most regression models estimate only a specific percentile speed, which is one of the main deficiencies in speed modeling. Tarris et al. reported that the loss of information due to speed data aggregation reduces the total variability and nature of the variability associated with the regression function; this loss may bias the influence of road geometrics (*6*). Tarris et al. propose that modeling the entire free-flow speed distribution may help to overcome the problem. Figueroa Medina and Tarko developed speed models for different percentiles by representing the percentile speed as a linear combination of the mean and standard deviation of the speed distribution (*7*). The models distinguish between the mean speed factors and the speed dispersion factors. Furthermore, in another publication by Figueroa Medina and Tarko, percentile-specific and site-specific random effects were included in the model formulation to avoid estimating biased parameters produced by unknown factors (*8*).

In a previous research study by Lobo et al., the authors presented a free-flow speed exponential model for curves and tangents based on the 85th-percentile speed observed at selected sites on Portuguese two-lane highways (*9*). This model already addresses some of the concerns raised in *Transportation Research Circular E-CI5I* (*1*), namely, the independence of the effects of speed predictors assumed by the linear regression models and the relatively few speed models developed for tangents. In the current research, the main objective is to go one step further and present a new operating speed model capable of predicting any percentile speed for a given curve or tangent. With an innovative approach to the operating speed modeling problem based on the econometric theory (*10, 11*), an operating speed frontier model (OSFM) is developed in this study.

The new model has two main distinctive features. First, it proposes that the maximum operating spot speed (*Vmax*), which is the speed adopted by the fastest driver in good weather and pavement conditions, be represented by a frontier function of the on-site geometrics (radius, length, grade, and cross-section width). Second, the deviations from the speed frontier attributed to non-geometric factors such as driving practices, vehicle technology, and road environment allow for the estimation of any percentile speed through the cumulative function of the one-sided disturbance.

METHODOLOGICAL APPROACH

Background Model

The stochastic frontier production model, introduced in 1977 by Aigner, Lovell and Smith (*12*) and by Meeusen and van den Broeck (*13*), is a widespread concept in the econometric analysis (*10*-*11*) and consists of a parametric approach to evaluate a firm's efficiency in the production process, that is, in the use of available resources (inputs) to obtain a new product or service (output). The model's functional form is represented by Equation 1.

$$\ln Y = \beta X + v - u \tag{1}$$

where

Y = output produced,
β = vector of input coefficients,
X = vector containing the logarithms of inputs,
v = noise term, and
u = one-sided distribution error.

The model is formed by one deterministic component, βX, and two disturbance components, the one-sided distribution error and the noise term. The noise term is the random error related to the model specification or the inadvertent omission of relevant inputs and errors in data collection (*11*). The probability of the noise term being favorable to production is assumed to be equal to the probability of its being unfavorable, so it takes the form of a normal and symmetric distribution, giving the random (i.e., stochastic) nature to the production frontier $exp(\beta X+v)$. Therefore, depending on the noise term, the stochastic frontier output can lie above or below the deterministic component $exp(\beta X)$. The stochastic frontier bounds the output from above, and the firms sitting below that frontier fail to achieve the ideal production rate. Thus, because the data are in log terms, the error u measures the percent deviation from the stochastic frontier – that is, the production inefficiency – as being always positive and taking the form of an asymmetric distribution. Half-normal, truncated normal, exponential, and gamma distributions have been suggested as possible distributions for this error (*12*, *14*). The model estimation is performed using the maximum likelihood method, which is more efficient in dealing with asymmetric distribution disturbances than the least squares estimator (*10*).

OSFM Formulation

The core idea of this study is the application of the stochastic production frontier approach to model the entire speed distribution on two-lane highways, and to draw a parallel between (a) production inputs and road geometric features, (b) produced output and practiced speeds, and (c) production inefficiency and speed variations due to non-geometric factors. Therefore, it is assumed that curves or tangents with the same geometric features (radius, length, grade, and cross-section width) are characterized by a *Vmax* depending on those features and corresponding to the speed of the fastest free-flow driver – that is, the least influenced by the non-geometric factors – in good weather and pavement conditions (not to be confused with a safety limit speed); hence, *Vmax* may be considered as a deterministic speed frontier. The drivers adopting lower speed values reflect the differences in driving behavior, vehicle technology, and road environment. Thus, the effects of the non-geometric factors, with the exception of the random effects, on the speed are suitable to be represented by the one-sided disturbance (u). The noise term (v) represents the random nature of the stochastic speed frontier (V^*), which is explained graphically in Figure 1.

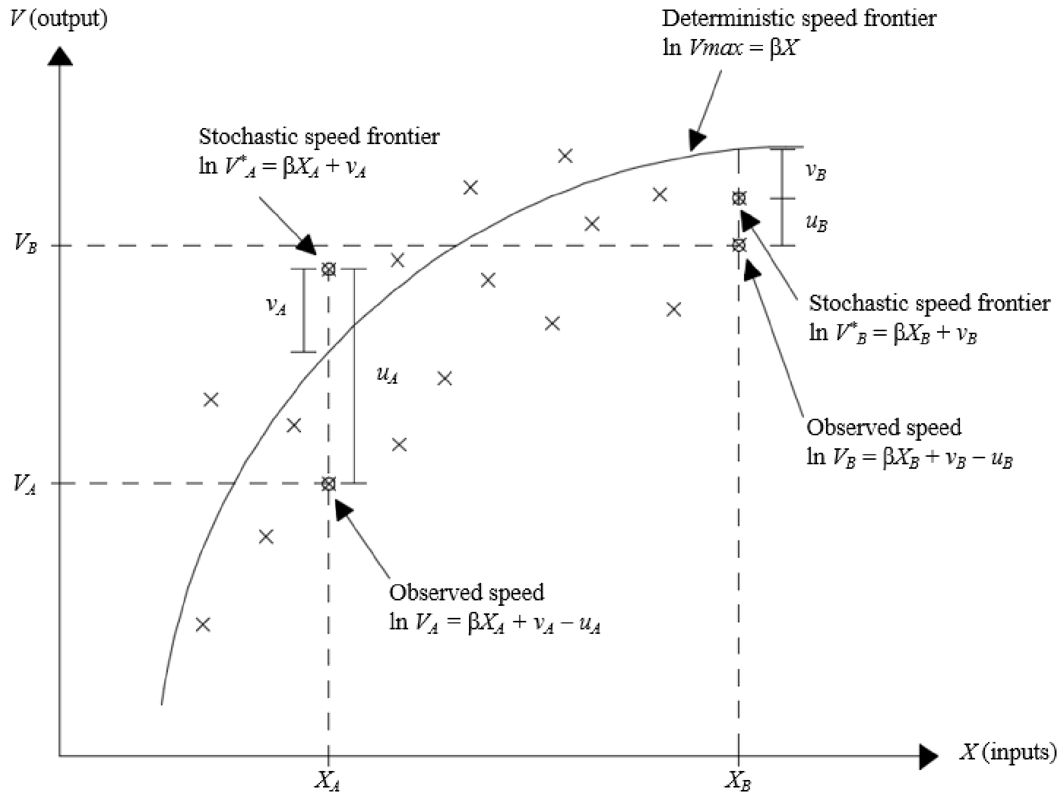

FIGURE 1 Stochastic speed frontier [based on work by Coelli et al. (*11*)].

In a previous operating speed study (*9*), the authors considered that the effects of road geometrics on speed are not cumulative but are dependent on the order of magnitude of practiced speeds. To comply with the previous assumption, the deterministic speed frontier takes the following exponential form:

$$Vmax_j = \exp\left(\beta_0 + \sum_{k=1}^{n_k} \beta_k \ln X_{jk}\right) \tag{2}$$

where

$Vmax_j$ = maximum operating speed in element j,
X_{jk} = geometric feature k of road element j, and
β_0, β_k = regression coefficients.

The stochastic frontier regression to estimate the variables' elasticities and the deviations from the stochastic frontier is given by the general expression in Equation 3.

$$V_{ij} = Vmax_j \times \exp(v_{ij}) \times \exp(-u_{ij}) \quad (3)$$

where

V_{ij} = speed of free-flow vehicle *i* observed in road element *j*,
v_{ij} = noise term for vehicle *i* in element *j*, and
u_{ij} = one-sided disturbance for vehicle *i* in element *j*.

The speed frontier $Vmax_j$ holds constant for all vehicles traversing a road element *j*, and the speed deviations from that frontier, caused by diverse speed choices, are represented by the one-sided disturbance. Thus, this disturbance allows for the estimation of any percentile speed for section *j* through the cumulative function of its distribution. Although other functional forms may be suited to the distribution of the one-sided disturbance (*12*, *14*), in this study, an exponential form is assumed because it is easier to use in a practical application, for example, compared with the half-normal distribution (*10*), which was tested without significant change in the results. For the distribution $f(u) = \theta.exp(-\theta u)$, where θ is the rate parameter of the exponential function, the cumulative function is given by $F(u) = 1 - exp(-\theta u)$, and the inverse transform is $u = (-1/\theta).ln(1 - F)$. Thus, the general formulation of the OSFM for the estimation of the *p*th percentile speed for a given curve or tangent is given by Equation 4.

$$Vp_j = Vmax_j \times \exp\left(\frac{1}{\theta} \ln p\right) \quad (4)$$

where Vp_j is the *p*th percentile speed in element *j* and *p* is the percentile value ($0<p<1$).

The maximum likelihood estimation of the exponential model is then applied to obtain the best parameter estimation by maximizing the log-likelihood function represented as

$$\ln L = N \ln \theta + \frac{N}{2}\theta^2 \sigma_v^2 + \theta \sum_{j=1}^{n_j} \sum_{i=1}^{n_i} (v_{ij} - u_{ij}) + \sum_{j=1}^{n_j} \sum_{i=1}^{n_i} \ln \Phi\left(-\frac{v_{ij} - u_{ij}}{\sigma_v} - \theta \sigma_v\right) \quad (5)$$

where

L = likelihood function,
N = total number of observations,
σ_v = standard deviation of the noise term, and
$\Phi(.)$ = standard normal distribution function.

APPLICATION OF THE MODEL

The database used to test the new model formulation is the same as that previously used to model the 85th-percentile speed for Portuguese two-lane highways (*9*). The case study road sections belong to five roads in Northern Portugal, N 14, N 101, N 105-2, N 206, and N 222. The selected sections are located outside the urban areas, and the marginal land use varies from the complete absence of construction (Figure 2a) to the presence of some isolated buildings (Figure 2b).

(a) (b)

FIGURE 2 Examples of considered road sections: marginal land use varies from (a) complete absence of construction to (b) presence of some isolated buildings.

Spot speed measurements were carried out during the day in clear weather conditions on 61 curves and 27 tangents, over a total of 116 km of road. The pavement of the selected sections was in good shape, with clearly visible markings and no cracks or potholes that may cause speed reductions. Vehicle speeds were recorded with traffic counters containing a Doppler radar sensor and placed at the approximate midpoint of the selected tangents and curves. Some procedures were used to disguise the equipment because drivers tended to brake in the presence of unfamiliar objects installed at the roadside. Because the model uses the grade as a speed predictor, speeds were collected separately for each direction. To ensure a homogenous sample for modeling purposes, the same number of free-flow vehicles – 102 vehicles – per section and direction were included in the sample, according to the *Highway Capacity Manual 2010* recommendation of a minimum of 100 measured speeds per site for operating speed studies, for a total of 17,952 observations (*15*). It is assumed that free-flow traveling conditions occur for a time gap between vehicles of at least 6 s, as proposed by Lobo et al. in a study conducted on Portuguese two-lane highways (*16*). The road alignment was reproduced in two steps: (a) collection of the GPS coordinates of the road (*x*,*y*,*z*) by using the instrumented vehicle of the Traffic Analysis Laboratory of the Faculty of Engineering of the University of Porto, and (b) adjustment of geometric elements to the collected points using a CAD software.

The prediction variables included in the OSFM are as follows: dummy variable for curves (*C*), radius (*R*), length (*L*), one-direction paved width (*PW*), dummy variable for medium-to-severe upgrades (*GUP*), and dummy variable for medium-to-severe downgrades (*GDN*). To comply with the model formulation, all the continuous variables are used in log terms.

To account for curves and tangents using the same mathematical expression, the dummy variable for curves is set to 1 for a curved section and to 0 for a tangent section. The radius is used only for curved sections and is nullified for tangent sections by being multiplied by the dummy for curves ($C \times lnR$). Because different impacts on speeds caused by the element length may occur between curves and tangents, the length is considered separately for each type of element. In the case of curved sections, the effects of the length variation on the operating speed are considered to be dependent on the value of the radius; this feature leads to the consideration of cross-effects of both variables ($C \times lnR \times lnL$), which are also nullified for tangent sections by the dummy for curves. Similarly, a dummy variable for tangents ($T = 1$ for tangents; $T = 0$ for curves) is created with the sole purpose of nullifying the tangent length for curved sections ($T \times lnL$). Studies such as Pérez Zuriaga et al. show asymptotical behavior of the operating speed in long tangents to a desired traveling speed (*17*). However, the winding nature of the case study roads reveals relatively small tangent lengths, varying from 161 m to 1055 m, with an average value of 345 m. Thus, in this application, *Vmax* in tangents cannot be assumed as a desired speed, but rather as a maximum operating speed conditioned by the tangent length.

The studied road sections are located in level or rolling terrain, and the continuous variable representing the grade (G) does not vary considerably within the sample; thus non-significant results are produced in the regression model. Similar results were obtained by Fitzpatrick et al. (*2*); however, these authors considered the grade as an important factor impacting the operating speed and tested the grade as a blocking factor, having found some differences for grades above 4%. To capture the effects of steeper hills and to improve the findings of previous work in which the grade was not considered (*9*), in this study, the grade values are aggregated in two dummy variables, *GUP* and *GDN*, being set to 1 if $G \geq 4\%$ and $G \leq -4\%$, respectively, and to 0 otherwise. *PW* is set as the sum of the lane and right shoulder widths. The representative average values for the sites in question are considered for the definition of the grade and cross-section variables. The statistics of the variables included in the model for the test sites are shown in Table 1.

TABLE 1 General Data on Curves and Tangents

Variable Description	Average	Standard Deviation	Minimum	Maximum	Relative Frequency (%)
Curves					
Speed of the free-flow vehicles (km/h)	56.6	14.2	10.0	151.0	n/a
Radius (m)	181.4	156.0	35.0	680.0	n/a
Length (m)	116.4	71.5	40.3	387.3	n/a
One-direction paved width (m)	5.5	1.6	3.4	16.3 [a]	n/a
Dummy for medium-to-severe upgrades	n/a	n/a	n/a	n/a	20.5
Dummy for medium-to-severe downgrades	n/a	n/a	n/a	n/a	20.5
Tangents					
Speed of the free-flow vehicles (km/h)	62.4	14.5	11.0	130.0	n/a
Length (m)	344.7	198.6	161.0	1,054.9	n/a
One-direction paved width (m)	4.9	1.3	3.1	9.6	n/a
Dummy for medium-to-severe upgrades	n/a	n/a	n/a	n/a	16.7
Dummy for medium-to-severe downgrades	n/a	n/a	n/a	n/a	16.7

[a] This exceptional value corresponds to one site featuring an unmarked parking area at the roadside.

Stochastic Frontier Regression Modeling

With the aim of modeling the operating speed for Portuguese two-lane highways, a model based on Equation 4 was performed between the speeds of the free-flow vehicles and the geometric features of the corresponding measurement sites. The model was estimated by using the maximum likelihood method (Equation 5) with the help of the econometric software *Limdep* (*14*). The regression coefficients and standard errors are shown in Table 2.

TABLE 2 Results of Stochastic Frontier Regression

Variable	Coefficient	Standard Error
Constant	3.930	0.036 [a]
C	-0.490	0.037 [a]
$C \times \ln R$	0.055	0.005 [a]
$C \times \ln R \times \ln L$	0.018	0.001 [a]
$T \times \ln L$	0.052	0.006 [a]
PW	0.033	0.006 [a]
GUP	-0.022	0.004 [a]
GDN	0.014	0.004 [a]
No. of observations = 17,952		
Log-likelihood = 2,000.435		
$\sigma_u = 0.166$		
$\sigma_v = 0.152$ [a]		
$\theta = 6.019$ [a]		

[a] Significant at the 1% level.

The data in Table 2 show that traversing a curved section reduces the operating speed; this fact is reflected by the negative coefficient of the dummy for curves. The radius and length also play important roles on speed impacts. The results confirm that the characteristics of the horizontal alignment are the most important factors affecting the operating speed.

The regression coefficients show that traveling in medium-to-severe upgrades reduces the speed by approximately 2.2%, whereas medium-to-severe downgrades increase the speed by approximately 1.4%. In terms of elasticity analysis, increasing the cross-section width by 10% while keeping the remaining variables constant causes a speed increase of 0.3%. Similarly, doubling the length in tangent sections produces a 5.2% speed increase. Because of the introduction of the cross-effects between the radius and length in curved sections, the corresponding elasticities are not constant. Therefore, the effects of these variables are quantified in absolute terms by using the following examples:

- A curve in level terrain with a radius of 150 m and sample mean values of the remaining variables of $L = 116.4$ *m* and $PW = 5.5$ *m* has an estimated *Vmax* of 67 km/h; doubling the radius produces an increase in *Vmax* of 7 km/h;
- A curve in level terrain with a length of 150 m and sample mean values of the remaining variables of $R = 181.4$ *m* and $PW = 5.5$ *m* has an estimated *Vmax* of 70 km/h; doubling the length produces an increase in *Vmax* of 5 km/h.

The OSFM proposed for the estimation of the maximum operating speed and the *p*th percentile speed in the curves or tangents of Portuguese two-lane highways is shown in Equations 6 and 7.

$$\begin{aligned} Vmax = \exp(&3.930 - 0.490 \times C + 0.055 \times C \times \ln R + 0.018 \times C \times \ln R \times \ln L + \\ &+ 0.052 \times T \times \ln L + 0.033 \times \ln PW - 0.022 \times GUP + 0.014 \times GDN) \end{aligned} \tag{6}$$

$$Vp = Vmax \times \exp\left(\frac{1}{6.019} \times \ln p\right) \tag{7}$$

where *Vp* is the *p*th percentile speed.

Percentile Speed Estimation

The OSFM proposed in Equations 6 and 7 allows for the estimation of any percentile speed by using road geometrics as speed predictors. Nevertheless, whenever the geometric features are unknown or not defined (e.g., in the planning stage), the model can still be used by replacing the deterministic frontier by an approximate or intended *Vmax* in Equation 7. Figure 3 shows the percentile speeds obtained for different values of *Vmax* for the observed conditions ($\theta = 6.019$).

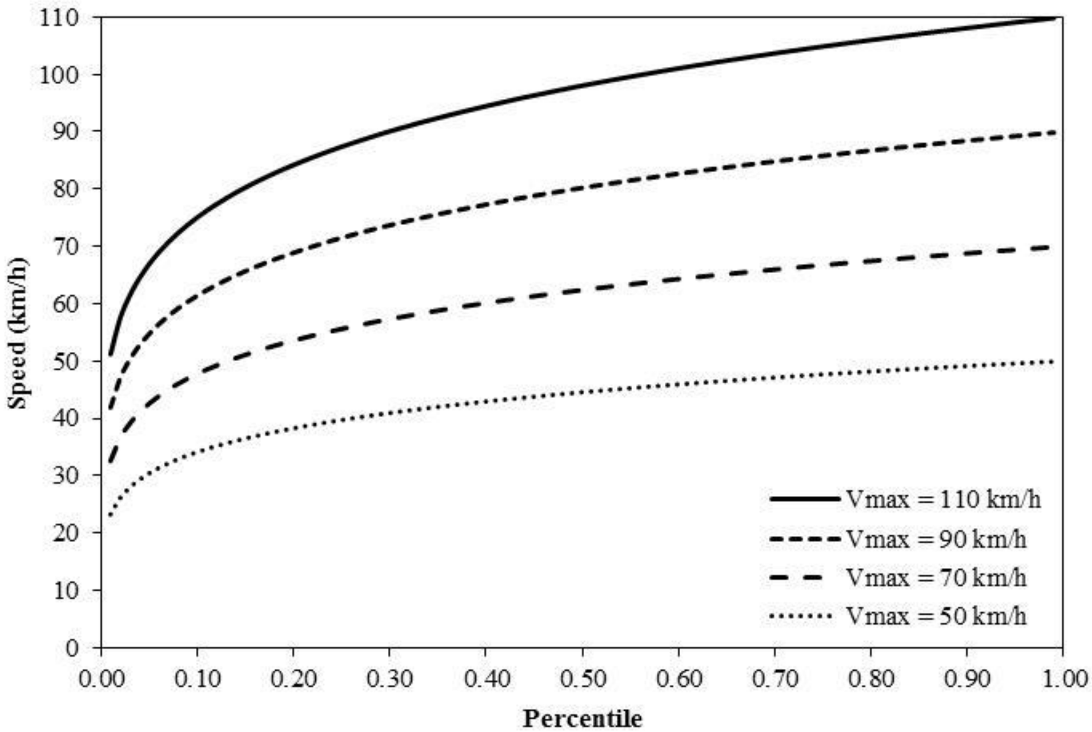

FIGURE 3 Percentile speeds estimated for diverse values of *Vmax*.

COMPARISON WITH EXISTING SPEED MODELS

In this section, the OSFM is compared with the model from previous research (*9*), as well as with other speed models, by means of a validation procedure. To validate the OSFM, speed measurements were conducted at three validation sites - two curves and one tangent - selected outside the original sample. The curves present very different geometric features; Curve 1 is significantly narrower than Curve 2. The observed percentile speeds were then compared with the predicted speeds resulting from the application of the models to those sites. The validation sites are described in Table 3.

TABLE 3 Generic Features of Validation Sites

Site characteristics	Curve 1	Curve 2	Tangent
Radius (m)	75.0	245.0	n/a
Length (m)	136.9	387.3	512.6
One-direction paved width (m)	4.7	5.9	5.8
Grade (%)	-4.0	5.0	-2.0

The models from other authors used for comparison with the OSFM were selected from among the models capable of estimating various percentile speeds. However, most of these models predict a limited number of specific percentile speeds. Thus, only the most common percentile speeds - *V15*, *V50* and *V85* - were estimated for the validation sites. Because of significant differences in the models' specifications, several additional variables had to be evaluated for the validation sites. The set of selected models is presented in Table 4.

The observed and estimated percentile speeds for the validation sites are presented in Figures 4 to 6. The differences in the models developed under distinct contexts led to some inconsistencies resulting from their application to the validation sites, probably because some of the variables may be outside the calibration range. The model from Figueroa Medina and Tarko (*7*) returned negative speed values for the narrower Curve 1, and consequently was not included in Figure 4. Moreover, the application of the models from Schurr et al. (*18*) and from Koeppel (*21*) to the validation tangent returned smaller values of *V85* than of *V50*. However, these estimates are shown in Figure 6 because the models provide good approximations to the observed *V85*.

Regarding the behavior of the OSFM, the estimated percentile speeds lie within the range of other models' results for all the validation test cases. The OSFM is the best percentile speed predictor for Curve 1, matching the observed values of *V15* and *V85* and estimating a *V50* which is greater than the observed value in only 1 km/h. The OSFM also provides the best estimations of *V15* and *V50* in the validation tangent, and *V15* in Curve 2 [also shown by Cardoso (*20*)], with deviations to the observed speeds of 6%, 9%, and 10%, respectively. The best estimate of *V50* of Curve 2 is given by Andueza (*19*), while the OSFM achieves the second position; speed deviations are of 2% and 11%, respectively. The estimate of *V85* in Curve 2 and in tangent represents the worst results of the OSFM, with speed deviations of 17% and 18%, respectively. Although other models may achieve worse results than the OSFM in these test cases, the best estimates are provided by Schurr et al. (*18*), with speed deviations of 3%.

The validation results show that the OSFM is the best percentile speed estimator in six out of nine test cases. The results also suggest that the OSFM performs especially well for narrow curves; the differences between the observed and predicted speeds are higher for wide curves and tangents. The winding nature of the Portuguese roads used in the model calibration may explain this behavior. Nevertheless, in a comparison of the OSFM with the model from Cardoso (*20*), also developed in Portugal, the OSFM provides better approximations to the observed percentile speeds in seven out of nine test cases, an equal approximation in one case, and a worse result in another case. The results are also consistent with the models from other countries. Therefore, the presented OSFM is an appropriate tool to estimate the operating speed on Portuguese two-lane highways, for which it was developed. Its structure has proven effective in speed prediction and may be calibrated for different contexts.

TABLE 4 Speed Models Used for Comparison with OSFM

Model (Location)	Equations [a]
Lobo et al. (*9*) (Portugal)	$V85=exp(3.999-0.626C+0.118C.lnR+0.065lnL+0.058lnPW+0.009lnELC-$ $-0.019lnB-0.036lnDI-0.043CV)$
Figueroa Medina and Tarko (*7*) (Indiana, USA)	$Vp,curve=47.664+3.44\times10^{-3}SD-2.639RES-2.541DC+7.954SE-0.624SE^2+$ $+4.158Z_p+0.236Z_p.DC-0.199Z_p.SE$ $Vp,tangent=57.137-0.071TR-3.082PSL_{50}-0.131GR-1.034RES+2.38\times10^{-3}SD-$ $-1.67\times10^{-6}SD^2-0.422INT+0.040PAV+0.394GSW+0.054USW-$ $-2.233FC+5.982Z_p+1.428Z_p.PSL_{50}+0.061Z_p.GR+0.292Z_p.INT-$ $-0.038Z_p.PAV-0.012Z_p.CLR$
Schurr et al. (*18*) (Nebraska, USA)	$V50,curve=67.4-0.1126\Delta+0.02243L+0.276PS$ $V50,tangent=51.7+0.508PS$ $V85,curve=103.3-0.1253\Delta+0.0238L-1.039G_1$ $V85,tangent=70.2+0.434PS-0.001307T_{ADT}$
Andueza (*19*)[b] (Venezuela)	$V50,curve\approx87.78-2251/R-739/R_a+0.02S$ $V50,tangent\approx87.65-2064/R_a+17.353\times10^{-3}L_a$ $V85,curve=98.25-2795/R-894/R_a+0.03S+9.308\times10^{-3}L_a$ $V85,tangent=100.69-3032/R_a+27.819\times10^{-3}L_a$
Cardoso (*20*) (Portugal)	$V15,curve=51.695-266.940/\sqrt{R}+0.43559V15,tangent-0.011272R+0.020297L$ $V15,tangent=22.893-0.01875B-0.08627GR+0.00599L-0.20053decl1+$ $+6.6083lfaixa1+1.3299lberma1$ $V50,curve=43.127-307.101/\sqrt{R}+0.41113Vp,tangent+3.1835lfaixa1$ $V50,tangent=24.741-0.03119B+0.00744L-0.21502decl1+8.7646lfaixa1+$ $+1.5345lberma1$ $V85,curve=61.849-435.322/\sqrt{R}+0.35167Vp,tangent+3.0560lfaixa1+$ $+7938.99/R^2+0.02207L$ $V85,tangent=37.146-0.04550B+0.01009L-0.19080decl1+9.0898lfaixa1+$ $+1.8999lberma1$
Koeppel (*21*) (Germany)	$V50=65.23+4.293b-0.0756CCR+0.0000364CCR^2$ $V85=0.065+0.484V50+1.869\times10^{-2}V50^2-1.349\times10^{-4}V50^3$

[a] where *ELC* = one-direction lateral clearance (m), *B* = bendiness (degrees/km), *DI* = density of intersections (No./km), *CV* = dummy for constrained visibility, *SD* = sight distance (ft), *RES* = dummy for residential driveways, *DC* = degree of curvature (degrees/100 ft of arc), *SE* = maximum superelevation rate (%), *Zp* = standardized normal variable corresponding to the *p*th percentile, *TR* = percentage of trucks, PSL_{50} = dummy for speed limit, *GR* = grade (%), *INT* = dummy for intersections, *PAV* = total paved width (ft), *GSW* = total gravel shoulder width (ft), *USW* = total untreated shoulder width (ft), CLR = total lateral clearance (ft), *FC* = dummy for flat curve, Δ = curve deflection angle (degrees), *PS* = posted speed (km/h), G_1 = grade of the previous tangent (%), T_{ADT} = average daily traffic (vehicles/day), R_a = radius of the previous curve (m), *S* = sight distance (m), L_a = length of the previous tangent (m), *decl1* = waviness (m/km), *lfaixa1* = two-lane width (m), *lberma1* = total shoulder width (m), *b* = total paved width (m), and *CCR* = curvature change rate (gon/km).

[b] Andueza developed average speed prediction models, which were considered as V50 models in this study.

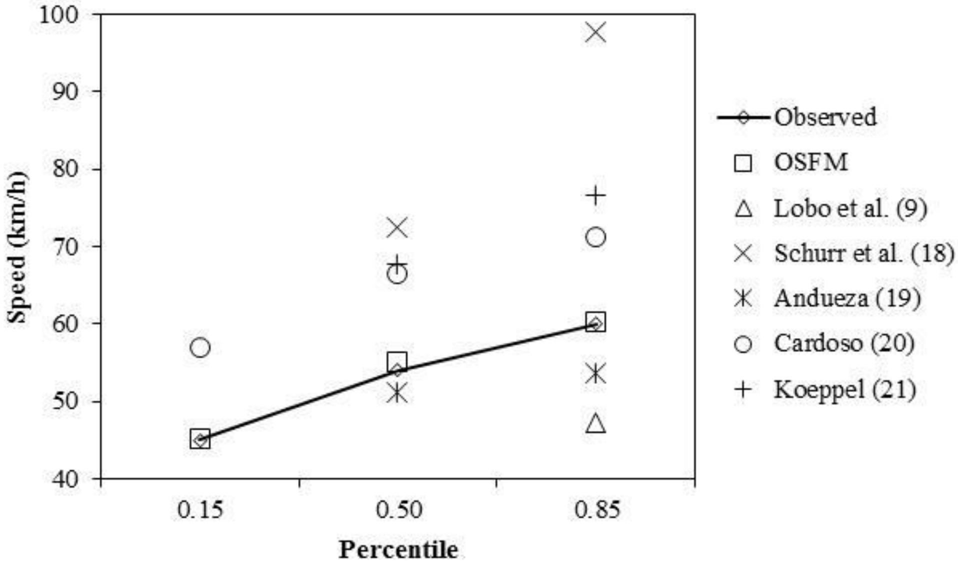

FIGURE 4 Comparison between percentile speed models for Validation Curve 1.

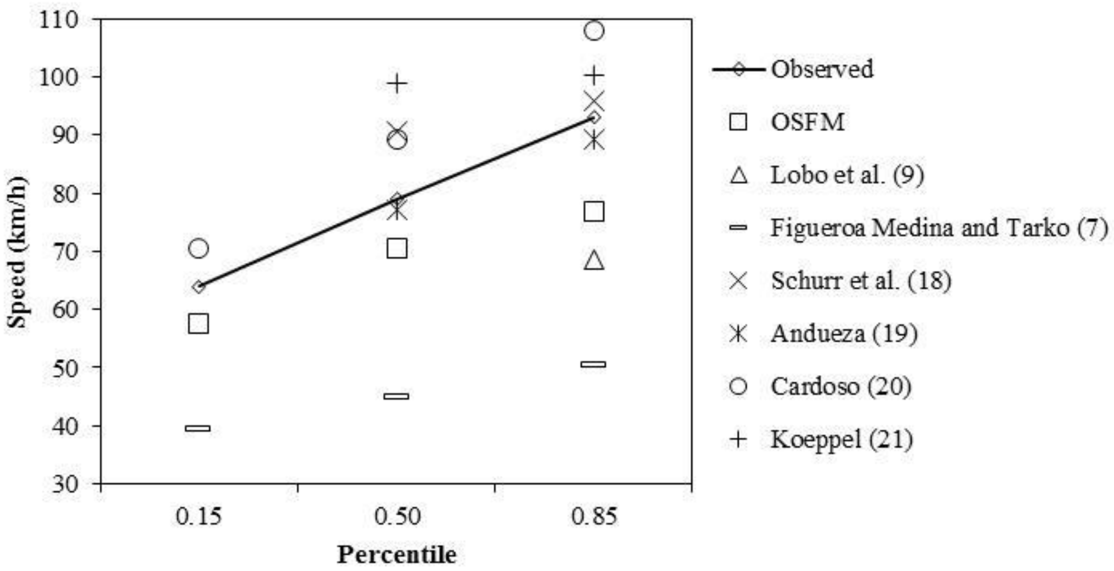

FIGURE 5 Comparison between percentile speed models for Validation Curve 2.

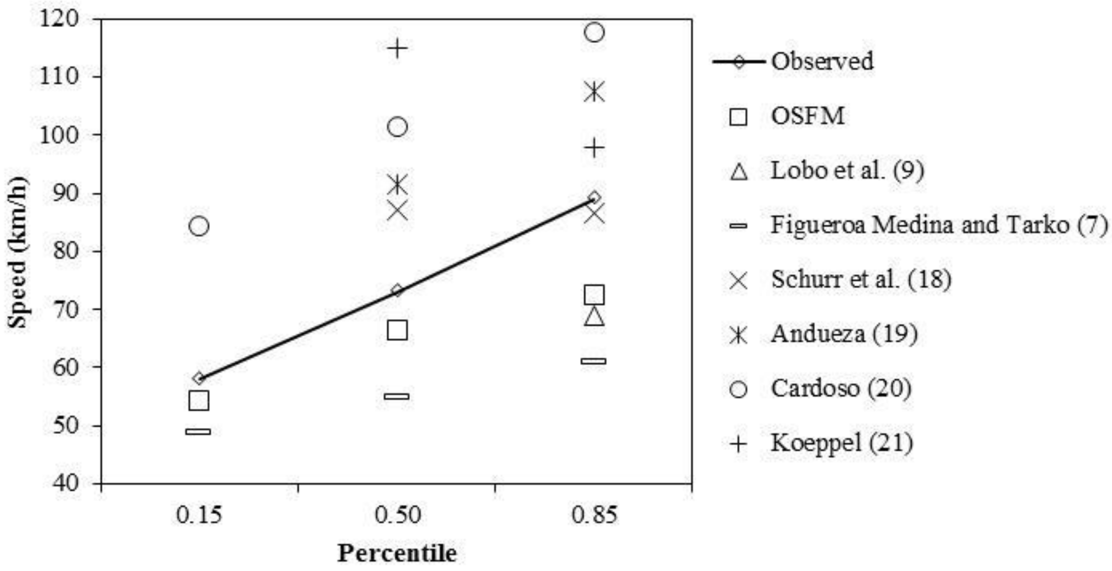

FIGURE 6 Comparison between percentile speed models for validation tangent.

CONCLUSIONS

Speed is a key performance measure in the economic and environmental analyses of roadway infrastructures. For this reason, researchers in road operations and design have developed numerous operating speed models that are applicable in different regions worldwide. Despite the comprehensive state of the art of speed modeling, there are still some deficiencies in these models, as pointed out by the TRB in a recent report (*1*). To address some of those concerns, the OSFM presented in this study follows an innovative stochastic frontier modeling approach and is capable of predicting any percentile speed. A deterministic speed frontier representing the maximum operating speed is established as a function of the local geometric features of the road, and the asymmetric disturbance is attributed to the differences in the speed choice due to driving practices, vehicle type, and road environment. Thus, percentile speeds may be estimated through the cumulative function of the one-sided disturbance.

Furthermore, the new model retains some of the distinctive features of the 85^{th}-percentile speed prediction model resulting from previous research (*9*), namely, the interaction between the geometric effects and the order of magnitude of the practiced speeds allowed by an exponential functional form, and the model applicability to both curves and tangents; thus it provides an alternative tool for the evaluation of design consistency.

The OSFM was calibrated and validated for the case study of Portuguese two-lane highways; it was confirmed that the impacts of horizontal alignment on speed are predominant in relation to grade and cross-section width. The authors recommend caution in the application of the OSFM in other contexts, especially in non-European countries, which have very different realities in terms of the driving culture, road design, and surrounding environment. However, because of the basic geometric features required to estimate the maximum operating speed and the capability of predicting any speed percentile, the model formulation is versatile enough to be replicated by practitioners for different regions across the globe; thus the model widely improves speed prediction capabilities.

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FLEXIBLE STOCHASTIC FRONTIER APPROACH TO PREDICT SPOT SPEED IN TWO-LANE HIGHWAYS

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A Flexible Stochastic Frontier Approach to Predict Spot Speed in Two-Lane Highways

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Abstract

The approach to spot speed prediction in two-lane highways followed in this study aims to evaluate the effects of a comprehensive set of speed factors, with a special focus on the geometric characteristics of the road segment to which the element belongs. Two flexible models were developed for different types of roads based on a stochastic frontier formulation in which the maximum operating speed is estimated as a function of road geometrics and the one-sided disturbance accounts for diversity in driving behavior and vehicle characteristics, allowing the estimation of any percentile speed. The models are applicable to horizontal curves and tangents and consider both on-site characteristics and aggregated variables characterizing the road segment. The results show a clear influence of segment features on different percentile spot speeds, revealing that recent driving experience and expectations about the quality of the geometric design influence the way a driver approaches a specific

road element. Additionally, this study contributes to addressing some of the limitations of existing speed models identified in the literature.

CE Database Subject Headings: Traffic Speed, Highway and road management, Stochastic Models, Portugal.

Author keywords: Spot speed, Two-lane highways, Road design, Stochastic frontier modeling.

Introduction

Operating speed is one of the most important factors in the evaluation and monitoring of roadway infrastructures. Drivers' evaluations of travel time, cost, convenience, and efficiency determine their route choice and are strongly influenced by their perceptions of the operating speeds of different routes. Likewise, many road design guides have been gradually implementing the use of operating speed prediction tools in the definition of road geometric standards, recommending that designers select a design speed with respect to road class, topography, and land use without neglecting driver expectancy (TRB 2011). Recommendations on maintaining a constant design speed over a substantial length of roadway are not new to road designers, but have proven to be insufficient to reduce speed variations between consecutive geometric elements, i.e., to ensure satisfactory design consistency. By anticipating the operating speed estimation in the design phase, some attributes that are not directly related to the design speed but which have a relevant impact on the operating speed (e.g., the cross-section width) may be properly defined. Therefore, the relationship between design speed and operating speed is currently regarded as a means to improve design consistency and safety performance (Fitzpatrick et al. 2003).

The relevance of the operating speed for setting roadway geometrics and other essential studies, such as the evaluation of the level of service, speed limit definition, and safety analyses, are at the heart of several efforts conducted by the research community, public authorities, and road operators to adequately predict road operating speeds and study its main drivers under different contexts. Those efforts have resulted in a wide array of tools for speed modeling (Fitzpatrick et al. 2000a; TRB 2011) and design consistency evaluation (Krammes et al. 1995; Gibreel et al. 1999; Fitzpatrick et al. 2000b) that are used by practitioners worldwide. Several issues arise from the complexity of studying driving speeds, however, and questions about the most relevant speed determinants and measures are frequently debated among researchers. Most studies consider a limited number of factors to predict specific speed measures (e.g., the 85^{th}-percentile speed), which is seen as a limitation of the existing speed models (TRB 2011).

This study introduces new spot speed prediction models that provide additional flexibility compared to existing models by considering the influence of road segment characteristics on the speeds practiced at a specific curve or tangent while also being capable of predicting any user-specified percentile. Therefore, the proposed models account for the interdependence between several on-site, upstream, and downstream geometric variables, and combine the speed effects of recent driving experience, instant response to road geometrics, and expectations about the road features. In addition, the Operating Speed Frontier Model (OSFM) formulation allows percentile speed estimation on the basis of an asymmetric disturbance term accounting for non-quantified factors, such as diversity in driving behavior, vehicle technology, and road environment.

This work builds on the authors' previous studies on operating speed modeling (Lobo et al. 2013; Lobo et al. 2014), bringing together the major accomplishments of those studies while enlarging their scope and applicability. The OSFM formulation was developed and successfully tested in Lobo et al. (2014). Compared to previous models, the new models combine the estimation of any percentile speed defined by the user with the consideration of the segment characteristics and allow speed predictions for roads with higher design speeds. For that purpose, the database was enlarged to cover all types of two-lane highways existing in Portugal, with design speeds ranging from 40 to 90 km/h. Two mathematical expressions are provided to predict spot speeds in roads with very different design standards, distinguishing roads with interchanges, without direct access to roadside properties, and overall design speeds of 80 to 90 km/h, which are usually classified in Portugal as Principal Itineraries or Complementary Itineraries (hereinafter called IP/IC roads), from roads with at-grade intersections, access to private properties, and lower design speeds, classified as National Roads (hereinafter called N roads).

This study addresses relevant issues noted by other researchers concerning the existing speed models (TRB 2011) specifically related to the limited applicability of models, the limitations of linear regression, and issues with data collection. The developed models aim to be flexible tools to support accurate speed predictions for a broader range of road conditions, contributing even further to improving speed prediction capabilities.

The remainder of the paper is structured as follows. First, the literature framework provides an overview of speed modeling practices and deficiencies in existing models. Then, the paper proceeds with the data description, which details the data collection procedures and the most relevant characteristics of the selected roads. The model description presents the OSFM formulation and the techniques used in model estimation. The model estimation presents two spot speed models obtained for different types of road. In the discussion of results, the effects of each variable used as speed predictor are analyzed, emphasizing the relevance of the road segment characteristics for different percentile speeds. The final section summarizes the main conclusions of this study.

Literature Framework

There is a large body of published literature presenting several approaches to modeling operating speed. Despite some inconsistencies between different sources, the definitions of operating speed provided by the main reference manuals are generally consistent and accepted by practitioners worldwide. The reference manual *A Policy on Geometric Design of Highways and Streets* (Green Book) (AASHTO 2011) defines operating speed as the speed at which drivers operate their vehicles during free-flow conditions, recognizing the 85^{th}-percentile of the speed distribution as the most frequently adopted operating speed measure. The *Manual on Uniform Traffic Control Devices* (MUTCD) (FHWA 2009) states that the operating speed may be represented by the average, pace, or 85^{th}-percentile speeds. In turn, the *Highway Capacity Manual* (HCM) (TRB 2010) proposes the similar concept of free-flow speed and suggests its measurement by averaging the speed of the observed vehicles.

Reference manuals and national guides for road design usually define design and operating speeds for segments rather than for specific design elements. When speed measurements are not possible, the HCM (TRB 2010) suggests adopting a base free-flow speed based on the design speed, posted speed limit, or operating speeds observed in similar facilities. Then, the free-flow speed is estimated for each road by reducing the base free-flow speed for the effects of the cross-section width and density of access points. In national guidelines, other effects are considered for operating speed prediction according to the local conditions, as is the case with the curvature change rate (CCR) and pavement width in Germany (FGSV 1995), and the bendiness and mean visibility in the UK (HA 2002). In turn, the Green Book (AASHTO

2011) proposes different design speeds according to the road functional classification and limits the speed differences between consecutive design elements to ensure design consistency. The official approach in Portugal follows a similar procedure (JAE 1994).

Spot speed prediction has also been a concern for the researchers, who have developed several models. Most models are based on conventional linear regressions and estimate specific percentile speeds considering a more or less comprehensive set of predictors. The *Transportation Research Circular E-C151* (TRB 2011) presents a good review of the existing speed models and their deficiencies.

The lack of flexibility among percentile-specific models is acknowledged as one of the main limitations of most studies. Tarris et al. (1996) referred that the loss of information due to speed data aggregation reduces the total variability and the nature of the variability associated with the regression function, which may bias the effects of road geometrics, proposing that modeling the entire free-flow speed distribution may help to overcome the problem. The only existing models that support a speed distribution were developed by Figueroa Medina and Tarko (2005). The models, obtained by ordinary-least-squares regressions, predict different percentile speeds that are represented by a linear combination of the mean and standard deviation of the speed distribution, distinguishing between the mean speed factors and the speed dispersion factors. In another study by Figueroa Medina and Tarko (2004), percentile-specific and site-specific random effects were included in the model formulation to avoid estimating biased parameters produced by unknown non-considered factors.

Despite also using the entire free-flow speed distribution, the authors' approach to percentile speed modeling (Lobo et al. 2014) is based on stochastic frontier models usually applied in the field of econometrics (Aigner et al. 1977; Meeusen and van der Broeck 1977). The OSFM is estimated using the maximum likelihood method to establish an upper speed frontier, which represents the speeds of the fastest free-flow drivers in good weather and pavement conditions as a function of road geometrics. Percentile speeds, representing deviations from the speed frontier attributed to non-quantified factors, such as the characteristics of drivers, vehicles, and the surrounding environment, are estimated through the cumulative function of the one-sided disturbance inherent to the model formulation.

Park and Saccomanno (2006) and Park et al. (2010) noted that few studies consider the interdependence between the speeds practiced in consecutive road elements. Thus, the frontier function used in this study considers on-site, upstream, and downstream geometric features as spot speed predictors. The exponential functional form accounts for the variations of the geometric effects with respect to the order of magnitude of speeds. Moreover, separate models are estimated for road types with very different design standards.

In terms of speed predictors, existing studies consider a wide array of variables characterizing the road geometry, environmental conditions, type of vehicle, and driver expectancy. The horizontal alignment is usually seen as the most important factor affecting speed, with some authors stating that the radius is the only variable producing a significant impact on driving speeds (Kanellaidis et al. 1990; Passetti and Fambro 1999; Misaghi and Hassan 2005).

Some authors noted that the vertical alignment has been less studied (Fitzpatrick et al. 2000a; Misaghi and Hassan 2005), perhaps due to its smaller impact on the speed of passenger cars. Nevertheless, studies by, e.g., Fitzpatrick et al. (2000a) and Gibreel et al. (2001) focused on the simultaneous effects of the horizontal and vertical alignments, proposing speed models categorized by vertical alignment conditions. Donnell et al. (2001) studied the primary influence of the grade on truck speeds, developing speed models for horizontal curves that account for the effects of the grades of the approach and departure tangents.

Roads' cross-sectional features were considered in studies such as Lamm and Choueiri (1987), Lamm et al. (1988), and Figueroa Medina and Tarko (2005). Melo et al. (2012) evaluated the speed reductions with respect to lane and shoulder widths using a driving simulator and compared the results with the HCM (TRB 2010).

Variables characterizing the entire road segment or just the upstream or downstream segments have been used to represent driver expectancy. McLean (1981) proposed the concept of desired speed to predict speeds on horizontal curves; the desired speed is influenced by the overall design standards, road function, trip purpose and length, and proximity to urban areas. Krammes et al. (1995) and Bonneson et al. (2007) used the speed on the approach tangent to represent the effects of recent driving experience on curve speed. The HCM (TRB 2010) proposes a speed reduction from the density of access points. The influence of the downstream alignment is frequently represented by parameters related to the sight distance (Andueza 2000; HA 2002). Other less used speed predictors include the element extension (Krammes et al. 1995; Voigt and Krammes 1996; Cardoso 1996; Schurr et al. 2002), the superelevation rate (Voigt and Krammes 1996; Gibreel et al. 2001; Bonneson et al. 2007), and the posted speed limit (Lamm et al. 1988; Schurr et al. 2002).

Despite the numerous speed factors reported in the literature, individual studies have usually found that significant effects on operating speeds are produced by limited sets of variables. Hassan (2004) and Nie and Hassan (2007) warned that the sites selected for speed measurements often lack variability in terms of road features or even preclude some of them, which may affect the validity and applicability of the models due to the excessive simplification of reality. The proposed OSFM formulation was developed to tackle the problem by taking into account a broad set of geometric effects and their interactions with the order of magnitude of speeds without neglecting the non-quantified factors, such as environmental conditions, driving behavior, and vehicle technology.

Model validity and applicability may also be affected by the sample size and data collection procedures. Nie and Hassan (2007) stated that the number of sites and the number of observations per site used in speed modeling is sometimes limited and that manual speed measurements can introduce bias errors because drivers may change their behavior if they perceive test equipment as speed enforcement. The cosine error associated with the use of radar guns is also a factor. To develop the models in this study, a great number of observations, approximately 23,000, was used, corresponding to the amount of vehicle speeds observed in seven two-lane highways with distinct design standards. Moreover, speed data were collected using discreet automatic traffic counters installed at the roadside, taking special care to calibrate their positioning using a test vehicle.

The new models are applicable to both curves and tangents, addressing the concerns raised by Polus et al. (2000) and Fitzpatrick et al. (2000a) about the need for additional research on tangent speeds. Thus, the model may support design consistency evaluation in Portugal, providing an alternative procedure in the national guidelines (JAE, 1994).

Data description

To calibrate the new speed models, speed and road geometrics data were collected in seven Portuguese two-lane highways, five of which are classified as N Roads (N14, N101, N105-2, N206, and N222), and two as IP/IC roads (IP2 and IC5). Spot speed measurements were made in 112 geometric elements, 77 curves, and 35 tangents located in selected road segments that reach a total length of 240 km. The selected sites are located outside urban areas, and the marginal land use varies from the complete absence of construction to the presence of some isolated buildings.

Because the aim was to evaluate not only the speed effects of the geometric characteristics observed at the test sites but also the effects of recent driving experience and expectations about the forthcoming road alignment, separate speed measurements were made for each direction to properly account for the upstream and downstream segments. To ensure a homogenous sample for modeling purposes, the same number of 102 free-flow vehicles was considered per site and direction, following the HCM (TRB 2010) recommendation of a minimum of 100 speed values measured per site for operating speed studies, resulting in a total of 22,848 observations. The percentage of heavy vehicles traveling in the case study roads is estimated at approximately 10% of the total number of vehicles. Free-flow traveling is established between vehicles that are separated by at least 6 seconds, as found in a study by Lobo et al. (2011) conducted in Portuguese two-lane highways. Automatic traffic counters (*VIACOUNT II*) containing a Doppler radar sensor, a real-time clock, and integrated data memory were used to record vehicle speeds and passing time. The equipment was installed at the roadside at the approximate midpoint of the selected curves and tangents. To ensure reliable speed measurements, the positioning of the traffic counters was calibrated using instrumented vehicle of the Traffic Analysis Laboratory of the Faculty of Engineering of the University of Porto. Because drivers may change their behavior upon perceiving test equipment as speed enforcement, the use of this type of equipment is especially adequate because its presence is barely noticeable and it does not require the presence of an operator while in use. Speed measurements were performed during the day in clear weather conditions. The pavement of the selected roads was in good shape, without cracks or potholes and with clearly visible markings.

The geometric characteristics were assessed in field measurements and/or by consulting road construction plans. When the construction plans were not available, the GPS coordinates of the road were collected with the instrumented vehicle and used the data to reproduce the road alignment via CAD software. The radius, length, grade, lane width, shoulder width, and lateral clearance were collected to characterize each of the selected elements. The grade and cross-section features were defined by representative mean values observed at each site. The length was discarded due to high correlations with other variables.

To characterize the upstream segments, the number of junctions and the deflection angle of each curve contained in each segment were collected. The grade observed at all the upstream segments is consistent with a level to rolling nature of the terrain. The upstream grade never surpasses a 3% value for an extension of 1 km or more, although higher grades may be present locally, as is the case for some spot speed measurement elements. According to the HCM (TRB, 2010), only the segments not attaining such limited conditions must be analyzed as specific grades due to relevant speed reductions. Therefore, the gradient of the upstream segment was not included in the speed modeling. In this study, 1-km-long upstream segments were used.

Assuming that the effects of downstream segments are related to the geometric characteristics that a driver is able to observe in every moment, the radii of the curves located within the decision sight distance were collected to characterize those segments. The decision sight distance was defined according to the Portuguese guide for road design (JAE 1994) and depends on the operating speed concept used by the same manual.

The collected data on road geometrics were subject to a preliminary treatment to derive the speed predictors considered in the models' development. The data treatment included the transformation of the continuous variables in log terms to comply with the OSFM formulation

(Lobo et al. 2014), as well as the creation of dummy variables to represent specific effects and/or to improve the model specifications. The speed predictors are described as follows:

- Dummy variable for curves (C) – Allows the use of the same mathematical expression for both types of geometric elements. C introduces a scale factor affecting the baseline formulation established for tangents (C = 0) to allow the estimation of curve speeds (C = 1);
- Curve radius ($C \times \ln R$) – Characterizes curves only. For tangents, this predictor is nullified by C;
- Dummy variables for medium-to-severe upgrades and downgrades (GUP and GDN) – Represents steeper hills; GUP and GDN are set to 1 if the ascending or descending grade is equal to or greater than 4%, respectively, and to 0 otherwise. The aggregation of grade data in GUP and GDN was made because of the non-significant results obtained with continuous variables in preliminary model test runs, which is probably associated with the predominating level to rolling nature of the terrain at the selected locations. Fitzpatrick et al. (2000a) obtained similar results but tested the grade as a blocking factor and obtained some differences for grades above 4%;
- One-direction paved width ($\ln PW$) – Represents the sum of lane and right shoulder widths;
- Extra lateral clearance ($\ln ELC$) – Represents the distance between the right shoulder external limit and any fixed object at the roadside;
- Bendiness ($\ln B$) – Represents the sum of the deflection angles of the horizontal alignment per kilometer in the upstream road segment;
- Dummy variable for intersections or interchanges (DDI) and density of intersections or interchanges ($DDI \times \ln DI$) – DI represents the number of intersections or interchanges

with other public roads per kilometer in the upstream road segment. Because *DI* is considered in log terms, the dummy variable *DDI* was created to nullify the effects of *DI* when no intersections are observed at the upstream segment (*DDI* = 1 if *DI* ≠ 0; *DDI* = 0 if *DI* = 0). Both the individual effects of *DDI* and the cross-effects between *DDI* and *DI* are considered in the model estimation;

- Dummy variable for constrained visibility (*CV*) – Represents the limitations of driver visibility due to the characteristics of the horizontal alignment of the downstream road section. *CV* is set to 1 if a driver is traversing a curve with a radius equal to or smaller than the absolute minimum radius (as defined by the Portuguese guidelines (JAE 1994)) or if there is such a curve within the decision sight distance, and set to 0 otherwise.

The statistics of the variables included in the models are shown in Tables 1 and 2 for N roads and IP/IC roads, respectively.

Table 1. General Data on Curves and Tangents: N Roads

Variable Description	Average	Standard Deviation	Minimum	Maximum	Relative Frequency (%)
Curves					
Speed (km/h) [a]	56.6	14.2	10.0	151.0	n/a
C	n/a	n/a	n/a	n/a	69.3
R (m)	181.4	156.6	35.0	680.0	n/a
GUP	n/a	n/a	n/a	n/a	20.5
GDN	n/a	n/a	n/a	n/a	20.5
PW (m)	5.5	1.6	3.4	16.3 [b]	n/a
ELC (m)	0.4	0.6	0.0	3.0	n/a
B (degrees/km)	239.7	172.4	13.8	854.7	n/a
DDI	n/a	n/a	n/a	n/a	94.3
DI (No./km)	3.4	2.0	0.0	10.0	n/a
CV	n/a	n/a	n/a	n/a	52.5
Tangents					
Speed (km/h) [a]	62.4	14.5	11.0	130.0	n/a
GUP	n/a	n/a	n/a	n/a	16.7
GDN	n/a	n/a	n/a	n/a	16.7
PW (m)	4.9	1.4	3.1	9.6	n/a
ELC (m)	0.3	0.5	0.0	1.7	n/a
B (degrees/km)	182.9	140.0	8.9	593.5	n/a
DDI	n/a	n/a	n/a	n/a	92.6
DI (No./km)	3.5	2.1	0.0	9.0	n/a
CV	n/a	n/a	n/a	n/a	20.4

[a] Measured for free-flow vehicles (gap ≥ 6 s).
[b] This exceptional value corresponds to one site featuring an unmarked parking area at the roadside.

Table 2. General Data on Curves and Tangents: IP/IC Roads

Variable Description	Average	Standard Deviation	Minimum	Maximum	Relative Frequency (%)
Curves					
Speed (km/h) [a]	99.1	20.0	12.0	203.0	n/a
C	n/a	n/a	n/a	n/a	66.6
R (m)	836.3	345.5	270.0	1,650.0	n/a
GUP	n/a	n/a	n/a	n/a	34.4
GDN	n/a	n/a	n/a	n/a	34.4
PW (m)	5.2	0.5	4.9	6.4	n/a
ELC (m)	0.5	0.6	0.0	1.3	n/a
B (degrees/km)	49.0	26.6	13.1	119.1	n/a
DDI	n/a	n/a	n/a	n/a	16.1
DI (No./km)	0.2	0.4	0.0	1.0	n/a
CV	n/a	n/a	n/a	n/a	6.5
Tangents					
Speed (km/h) [a]	102.4	21.4	12.0	183.0	n/a
GUP	n/a	n/a	n/a	n/a	31.3
GDN	n/a	n/a	n/a	n/a	31.3
PW (m)	5.0	0.5	4.0	6.1	n/a
ELC (m)	0.5	0.5	0.0	1.2	n/a
B (degrees/km)	25.3	27.4	0.0	100.2	n/a
DDI	n/a	n/a	n/a	n/a	6.3
DI (No./km)	0.1	0.2	0.0	1.0	n/a
CV	n/a	n/a	n/a	n/a	6.3

[a] Measured for free-flow vehicles (gap ≥ 6 s).

The prominent differences between N roads and IP/IC roads, which in this study led to the development of separate speed models, have a historical background. Until the 1970s, the primary goal of road construction in Portugal was to provide road connections between all the country's towns and villages. By focusing on spatial coverage while containing construction costs, the design principles followed at that time relegated the operational performance to a secondary plan; the design speed was usually highly dependent on the topography. The great majority of N roads in Portugal were built prior to the 1970s. In the 1980s, the country was experiencing a major social and economic shift due to the end of a period of political instability stemming from the 1974 revolution and Portugal's accession to the European Union. These transformations contributed to increased population mobility needs that the existing road network was no longer capable of supporting. With the spatial coverage of the entire territory almost accomplished, but facing increasing problems related to traffic flow and safety, since the 1980s, the Portuguese Government has promoted the construction of new freeways and 2-lane highways aimed to support faster and safer connections between the country's main cities and with the Spanish border. Most of the new two-lane highways have been classified as IP/IC roads, are compliant with up-to-date design standards, and represent an enormous step forward in the quality of road geometric alignments. Fig. 1 portrays the typical environment of N roads (Fig. 1(a)) and IP/IC roads (Fig. 1(b)) though the representation of two case-study roads.

(a) (b)

Fig. 1. (a) Example of N road: N101; (b) example IP/IC road: IC5

The five N roads selected in this study are representative of the diversity of N roads existing in Portugal. The design speeds vary from 40 to 70 km/h and the junctions are, with a few rare exceptions, at-grade intersections. Direct access to roadside properties is allowed and variables such as the lateral clearance and the density of intersections exhibit significant variations with the marginal land use (see Table 1). Some curves have a smaller radius than the value recommended by the Portuguese guidelines currently in force (JAE 1994), which may bring negative consequences to the comfort and safety of car occupants and affects drivers' sight distance. The lane width is also sometimes smaller than the minimum value of 3.5 m defined by the same manual.

Compared to the authors' previous research (Lobo et al. 2013; Lobo et al. 2014), the database was enriched in this study with data from two recently built IP/IC roads. These roads are representative of the two-lane IP/IC roads existing in Portugal featuring overall design speeds of 80 to 90 km/h. The undifferentiated treatment given in this study to IP and IC roads is related to the homogenous geometric features that characterize both types of roads and that set them apart from the N roads. In fact, the distinction between IP and IC roads is based on functional characteristics, such as the traffic volume, predominant types of journey, and interaction with the remaining network, rather than on geometric standards. The wider curves, no direct access to roadside properties and grade separation at junctions resulted in the observation of much higher values of average spot speed on IP/IC roads (see Table 2).

Model description

The speed distribution observed at a particular road location reflects the dispersion of the practiced speeds that arises from different interactions between drivers, vehicles, and instant/permanent conditions of the road and the surrounding environment. In other words, practiced speeds may vary with a wide array of factors characterizing the three components of road transport: road, driver, and vehicle. Because the permanent characteristics of the road, mainly related to the geometric design, are the common denominator for all the drivers observed at that location, it is possible to state that the highest speed value is the least influenced by the speed-restrictive characteristics associated with the driver, vehicle, and road environment. In other words, the speed practiced by the fastest driver is mainly dependent on road geometrics.

The OSFM approach, first described and tested in Lobo et al. (2014), consists of applying a stochastic frontier model formulation, commonly associated with the econometric analysis, to estimate an upper speed frontier based on the total number of speed observations registered at all test sites. This speed frontier is a function of road geometrics characterizing the permanent conditions of the road, which are widely accepted by the scientific community as the main drivers influencing speeds and are usually less subjective and easier to measure than driver, vehicle, and environmental characteristics. The speed frontier resulting values correspond to the estimated speed for the fastest free-flow driver for each possible combination of geometric features under good weather and pavement conditions. Because the estimated frontier represents an upper limit of the operating speeds, it is hereafter referred to as maximum operating speed (*Vmax*). Note that *Vmax* is a newly introduced speed concept arising from the statistical processing of operating speed data; hence, it should not be confused with maximum speeds associated with imminent crash situations, such as skidding and overturning. *Vmax* holds constant for all vehicles traversing a given road element and is given by Eq. (1).

$$Vmax_j = \exp\left(\beta_0 + \sum_{k=1}^{n_k} \beta_k \ln X_{jk}\right) \tag{1}$$

where $Vmax_j$ = maximum operating speed in element j; X_{jk} = geometric feature k of the road element j; and β = regression coefficients. The exponential formulation represents the assumed principle according to which the effects of geometric factors are not cumulative but are dependent on the order of magnitude of practiced speeds.

The main advantage of the OSFM lies in its capability to provide any percentile speed estimation from *Vmax* by means of an asymmetric disturbance. In addition to the normally distributed disturbance assumed in most regression models, which supports the stochastic nature of the speed frontier and represents random errors related to data collection and the model specification, the OSFM considers a second, asymmetrically distributed disturbance term that allows the estimation of speeds for drivers acting below the speed frontier *Vmax* for each combination of road geometrics. The asymmetric disturbance is suitable for representing the non-quantified speed factors related to the characteristics of vehicles, drivers, and the surrounding environment. Subsequently, the cumulative distribution function of the asymmetric disturbance allows the estimation of any percentile speed. In Lobo et al. (2014), an exponential distribution was proposed for the one sided disturbance, such as $f(u) = \theta \, . \exp(-\theta u)$, where θ is the rate parameter of the exponential function. The cumulative function is given by $F(u) = 1 - \exp(-\theta u)$, and the inverse transform is $u = (-1/\theta) \, . \ln(1 - F)$. Thus, the general form to estimate the pth percentile speed at a given road location is shown in Eq. (2).

$$Vp_j = Vmax_j \times \exp\left(\frac{1}{\theta}\ln p\right) \tag{2}$$

where Vp_j = pth percentile speed in element j; and p = percentile value ($0 < p < 1$).

The OSFM is estimated using the maximum likelihood method, which is more efficient in managing asymmetric disturbances than the least squares estimator (Greene 2008). The best parameter estimation is obtained by maximizing the log-likelihood function represented in Eq. (3).

$$\ln L = N \ln \theta + \frac{N}{2}\theta^2 \sigma_v^2 + \theta \sum_{j=1}^{n_j}\sum_{i=1}^{n_i}\left(v_{ij} - u_{ij}\right) + \sum_{j=1}^{n_j}\sum_{i=1}^{n_i} \ln \Phi\left(-\frac{v_{ij} - u_{ij}}{\sigma_v} - \theta\sigma_v\right) \tag{3}$$

where L = likelihood function; N = total number of observations; σ_v = standard deviation of the noise term; and $\Phi(.)$ = standard normal distribution function.

Model estimation

To calibrate the new spot speed models for Portuguese two-lane highways, two stochastic frontier regressions based on Eq. (2) are performed between the speeds of the free-flow vehicles and the road geometrics, one regression using data from IP/IC roads and another using data from N roads. Model estimations are made with the help of the econometric software *Limdep* (Greene 2007), using the maximum likelihood method. A preliminary single model estimation was tried using the complete dataset; however, several variables were not statistically significant. In the two-model approach, few variables are removed from the models due to the lack of statistical significance at 5% level, namely *DDI* in both models and *GUP*, *ELC*, and *DDI* × ln *DI* in the IP/IC model. The regression modeling results are presented in Tables 3 and 4 for N roads and IP/IC roads, respectively.

Table 3. Results of the Stochastic Frontier Regression: N Roads

Variable	Coefficient	Standard Error
Constant	4.360	0.016 [a]
C	-0.694	0.016 [a]
C × ln *R*	0.122	0.003 [a]
GUP	-0.014	0.004 [a]
GDN	0.021	0.004 [a]
ln *PW*	0.079	0.007 [a]
ln *ELC*	0.008	0.001 [a]
ln *B*	-0.027	0.002 [a]
DDI × ln *DI*	-0.036	0.003 [a]
CV	-0.049	0.004 [a]

Note: No. of observations = 17,952; Log-likelihood = 2,026.760; σ_u = 0.170; σ_v = 0.149; θ = 5.880.
[a] Significant at 1% level.

Table 4. Results of the Stochastic Frontier Regressions: IP/IC Roads

Variable	Coefficient	Standard Error
Constant	4.636	0.050 [a]
C	-0.608	0.072 [a]
C × ln *R*	0.086	0.011 [a]
GDN	0.041	0.006 [a]
ln *PW*	0.070	0.031 [b]
ln *B*	-0.003	0.001 [b]
CV	-0.055	0.015 [a]

Note: No. of observations = 4,896; Log-likelihood = 909.043; $\sigma_u = 0.146$; $\sigma_v = 0.149$; $\theta = 6.861$.
[a] Significant at 1% level.
[b] Significant at 5% level.

The model for spot speed prediction in N roads in Portugal is represented by Eqs. (4) and (5), used for the estimation of *Vmax* and the *p*th percentile speed (*Vp*), respectively.

$$\begin{aligned} Vmax = \exp(&4.360 - 0.694 \times C + 0.122 \times C \times \ln R - 0.014 \times GUP + 0.021 \times GDN + \\ &+ 0.079 \times \ln PW + 0.008 \times \ln ELC - 0.027 \times \ln B - 0.036 \times DDI \times \ln DI - 0.049 \times CV) \end{aligned} \tag{4}$$

$$Vp = Vmax \times \exp\left(\frac{1}{5.880} \times \ln p\right) \tag{5}$$

Similarly, the model for speed prediction in IP/IC roads is given by Eqs. (6) and (7).

$$\begin{aligned} Vmax = \exp(&4.636 - 0.608 \times C + 0.086 \times C \times \ln R + 0.041 \times GDN + 0.070 \times \ln PW - \\ &- 0.003 \times \ln B - 0.055 \times CV) \end{aligned} \tag{6}$$

$$Vp = Vmax \times \exp\left(\frac{1}{6.861} \times \ln p\right) \tag{7}$$

The OSFM formulation was tested and successfully validated in Lobo et al. (2014) by means of a comparison with other speed models existing in the literature. Nevertheless, it was tested in this study if the consideration of new sites and variables does not affect the accuracy of speed estimations, using the most known operating speed measure, i.e., the 85th-percentile speed (*V85*). First, the mean value of the observed *V85* was computed for different groups of sites within the sample (*V85o*). All the tangents belonging to each type of road correspond to one group. In addition, some curves were grouped according to the type of road and range of radii, because the number of curves with the same radius were not enough to extract representative values of *V85o*. Subsequently, the models in Eqs. (4) to (7) were applied to estimate *V85* for each group of sites, using the mean observed values of speed predictors (*V85e*). The results are presented in Fig. 2.

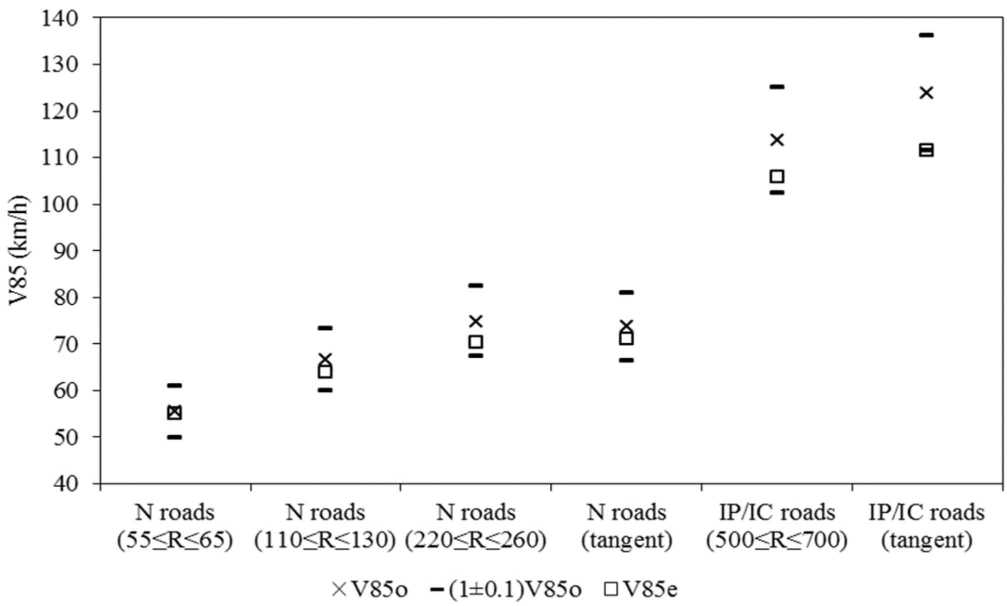

Fig. 2. Comparison between observed and estimated *V85*

The differences between *V85o* and *V85e* vary from 1.0% in curves of N roads with radii between 55 and 65 m to 9.9% in tangents of IP/IC roads. The application of the model for IP/IC roads result in larger speed deviations from the observed values compared to the model for N roads, probably because of an increased difficulty in the model's fit supported by speed data with higher dispersion. Nevertheless, for all test cases, *V85e* is within a margin of error of 10%, which represents the maximum error usually assumed at spot speed data collection, indicating that the new models are still capable of providing satisfactory operating speed predictions.

Discussion of results

Individual effects of speed predictors on spot speeds

The model functional form allows the interpretation of the coefficients of the continuous variables as elasticities. The results in Tables 3 and 4 show that the on-site geometrics are the most important factors affecting the operating speed. The negative coefficients of *C* reflect that operating speeds are lower in curves than in tangents, notwithstanding the value of *R*. Additionally, doubling the radius while keeping the remaining variables constant would increase *Vmax* in curves by 12% for N roads and 8% for IP/IC roads. Higher impacts occur in roads with lower design speeds, i.e., in roads with smaller radii values.

In terms of the vertical alignment, medium-to-severe downgrades would increase *Vmax* by 2.1% in N roads and by 4.1% in IP/IC roads. Medium-to-severe upgrades would reduce *Vmax* by 1.4% in N roads, not producing a statistically significant result for IP/IC roads, probably because operating speeds are much higher and passenger cars, which form approximately 90% of the collected sample, do not suffer a significant speed reduction in the ascending grades.

The results for the cross-sectional variables show that increasing *PW* 10% while keeping the remaining variables constant would positively affect *Vmax* 0.8% and 0.7% for N roads and for IP/IC roads, respectively. An increase of 10% in *ELC* while keeping the remaining variables constant would have a very small impact of 0.1% in *Vmax* for N roads. *ELC* did not produce a statistically significant result for IP/IC roads.

Regarding the upstream features, the negative elasticities of *B* reveal that halving this variable would cause a speed increase of approximately 3% in N roads and 0.2% in IP/IC roads. These results are consistent with those obtained for the curve radius, i.e., improving the quality of the horizontal alignment produces higher impacts on the operating speed for roads with lower geometric standards.

In IP/IC roads, the density of interchanges did not produce statistically significant results, probably due to the lack of interchanges in the 1-km upstream segment of most observations and by the dubious impact of this type of junction on the speed of through traffic due to the absence of crossing conflict points. The density of intersections on N roads has negative effects on *Vmax*, as confirmed by the negative coefficient of $DDI \times \ln DI$. Doubling the number of intersections while keeping the remaining variables constant would produce a decrease in *Vmax* of approximately 4%. The dummy variable *DDI* as a standalone variable did not produce a statistically significant result because of the accessibility provided by N roads: only approximately 6% of the selected sites present no intersections at the corresponding upstream segments.

The downstream segment characterizing variable *CV* shows that drivers reduce their speed when they see a tight curve downstream from their location. Reductions in *Vmax* are of approximately 5% for both types of road.

The rate parameter θ is lower for N roads ($\theta = 5.880$) than for IP/IC roads ($\theta = 6.861$). Therefore, percentile speed relative deviations from *Vmax* are smaller in the latter case, meaning that the higher the design speed, the lower the operating speed dispersion.

Speed effects from the introduction of road segment characteristics

To provide a better understanding of the spot speeds impacts caused by the characteristics of the upstream and downstream segments, a sensitivity analysis based on speed estimations for a set of generated scenarios is provided. Each scenario is characterized by a different combination of segment characteristics, varying between the sample minimum and maximum values to represent different harshness levels of the road alignment. The element geometrics are kept constant at the sample mean values. The scenarios are described as follows: S1 represents the best-case scenario, minimizing the negative effects and maximizing the positive effects of the upstream segment on spot speeds; S2 represents the average-case scenario, in which the upstream variables assume the sample mean values; S3 is the opposite of S1; S4 is the worst-case scenario, adding to S3 the effect of the downstream constrained visibility.

The models in Eqs. (4) to (7) were used to estimate *V85*. The differences in *V85* between different scenarios provide a more tangible way to analyze the upstream and downstream effects than the coefficients/elasticities of variables affecting *Vmax*. Table 5 provides an overview of the scenarios and speed predictions for curves (*V85c*) and tangents (*V85t*).

Table 5. Scenarios for Sensitivity Analysis of the Segment Characteristics

Scenario (Road Type)	B	DI	CV	V85c (km/h)	V85t (km/h)
S1 (N)	SMin	SMin	0	75.9	80.6
S2 (N)	SMean	SMean	0	67.3	71.0
S3 (N)	SMax	SMax	0	62.5	66.5
S4 (N)	SMax	SMax	1	59.5	63.3
S1 (IP/IC)	SMin	n/a	0	109.0	114.3
S2 (IP/IC)	SMean	n/a	0	108.5	111.6
S3 (IP/IC)	SMax	n/a	0	108.2	111.2
S4 (IP/IC)	SMax	n/a	1	102.4	105.2

Note: SMax = sample maximum; SMean = sample mean; SMin = sample minimum.

In absolute terms, the values of *V85c* and *V85t* show evidence of relevant contributions of the segment variables to the speed practiced at a given element, accounting for the driver's recent driving experience and expectations about the downstream geometric alignment. In Table 5, it is possible to observe that the estimated impacts on spot speeds due to the upstream factors present a variation of 14 km/h from S1 to S3 in N roads. IP/IC roads present a much smaller variation of just 3 km/h, reflecting the homogeneity of characteristics of this type of road. Considering the constrained downstream visibility (S4), spot speeds may be affected by an additional value of 3 km/h and 6 km/h, respectively. The speeds obtained in S2 are closer to

S3 than to S1, i.e., in average terms, the geometric characteristics of the sample roads are closer to the more restrictive scenario. The results in Table 5 also show that speed reductions from S1 are greater in tangents than in curves, where drivers already travel at lower speeds due to the effects of the horizontal curvature. The upstream effects are more relevant in N roads, where the greater variability of road geometrics may induce some additional caution in spot speed choice. In turn, the downstream constrained visibility seems to affect more driving speeds on IP/IC roads, where such situations are uncommon and to a certain extent unexpected.

Conclusions

The increasing relevance of speed as a key indicator for design control and operational analysis of roadway infrastructures has strengthened the need for more versatile speed prediction tools. Despite the valuable contributions of road operations researchers, legislators, and practitioners to operating speed modeling, there is still a room to improve knowledge in this field and to fill the gaps identified in the literature (TRB 2011).

The main objective established for this study was to provide a flexible tool to provide accurate spot speed predictions in two-lane highways for a broad range of situations. To do so, the developed approach addresses some of the major limitations of existing speed models related to the preclusion of some relevant variables and the ability to estimate only specific percentile speeds; most of the existing spot speed models estimate the 85th-percentile speed as a function of local geometric features, mainly related to the horizontal curvature. Thus, the OSFM formulation was used to calibrate new spot speed models capable of predicting any user-specified percentile in curves or tangents on the basis of element and segment geometric characteristics. A deterministic speed frontier representing the maximum operating speed is established as a function of the road geometrics. The asymmetric disturbance reflects the differences in speed choice due to driving practices, vehicle type, and road environment. The cumulative function of the asymmetrical disturbance distribution allows the estimation of percentile speeds.

Model calibration was achieved using the entire speed distribution of approximately 23,000 free-flow vehicles collected on seven Portuguese roads with a great diversity of characteristics, resulting in two separate models for N roads, featuring intersections and accesses to roadside properties, and IP/IC roads, featuring interchanges and no marginal access. The results confirm the primary influence of the local effects produced by the horizontal and vertical alignments and the cross-section characteristics; however, the upstream and downstream features also play an important role in the way a driver approaches a specific curve or tangent. To shed light on the relevance of these variables, a set of scenarios reflecting different road conditions was created, allowing to observe that that the upstream characteristics, reflecting the recent driving experience, may reduce the spot speed in around 14 km/h, while the downstream constrained visibility, reflecting the driver's perception of the design quality of the downstream segment, may reduce the speed up to an additional 6 km/h.

The models were calibrated for the road conditions observed in Portugal, where it is possible to provide speed predictions for all types of non-mountainous two-lane highways. In other contexts, especially non-European countries, these models should be applied with caution. Nevertheless, the model formulation is sufficiently versatile to be replicated by practitioners across the globe for a broad range of road conditions. This research delivers one of the most flexible spot speed prediction tools to date, which considers the interactions between segment and on-site geometrics, is capable of predicting any percentile speed, is applicable to curves and tangents of different types of roads, and addresses some major limitations of such models identified in the literature concerning the formulation, calibration, and applicability, thus widely improving speed prediction capabilities. This study presents the authors' latest achievements in spot speed modeling and builds a basis for research on speed modeling in road segments planned for the near future.

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SPEED PREDICTION IN SEGMENTS OF TWO-LANE HIGHWAYS

PAPER 6 Lobo, A., M. Amorim, C., Rodrigues, and A. Couto. Speed Prediction in Segments of Two-Lane Highways. Submitted for publication, 2017.

Speed Prediction in Segments of Two-Lane Highways

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Abstract

Most of the existing operating speed statistical models are applicable to individual design elements, particularly horizontal curves and tangents. A segment approach to operating speed has rarely been followed, with a few exceptions mainly related to the performance assessment of urban and freeway corridors, or design consistency studies using speed profiles built from successive design elements. This study introduces a new model to predict operating speeds in segments of two-lane highways. The maximum operating speed is given by a stochastic frontier function of the average daily traffic and road geometrics; the asymmetric disturbance accounts for the diversity in driving behavior and vehicle characteristics, allowing estimating

any percentile speed. The model was calibrated using probe vehicle data from non-congested roads. The accuracy of the average daily traffic in representing the actual driving conditions was further validated using simultaneous speed-traffic measurements. The new model aims to be a valuable tool for the practitioners to perform a preliminary design consistency evaluation during the design stage, as well as to support the definition of speed limits.

CE Database Subject Headings: Traffic Speed, Highway and road management, Stochastic Models, Portugal.

Author keywords: Operating speed, Road segments, Two-lane highways, Road design, Stochastic frontier modeling.

Introduction

Increasing efforts to understand and predict operating speeds in roadway facilities have been developed across the past decades, following the tendency of researchers and practitioners to use the operating speed as an instrument to define road geometrics and promote design consistency. Most of the existing speed models, proposed either in academic studies or in official guidelines, have focused on the purely geometric effects on driving speeds, exploring, in individual design elements, the relations between geometric parameters and the speeds practiced under free-flow conditions. The *Transportation Research Circular E-C151* (TRB 2011) provides a good review on such models. These models are usually based on spot speed measurements, which are relatively easy to implement. The minimum of one speed sensor, e.g., a radar sensor or a loop detector, is required to obtain numerous observations at a specific location. From this data, it is possible to calculate the time mean speed, i.e., the arithmetic mean of vehicles' speeds, or any desired percentile speed. Depending on the type of sensor, it may be reallocated to another survey element at any time.

Speed estimations in road segments, i.e., over a length of roadway, are less common across the literature, perhaps because they generally involve more complex procedures of data collection and treatment than spot speed estimations. A few official guidelines for road design propose different approaches to estimate and/or define operating and design speeds. In the UK, both operating and design speeds are defined on the basis of geometric variables, particularly the bendiness and mean visibility observed on a minimum 2-km-long segment (HA 2002). The same principle is followed in Germany, where the operating speed is determined by the curvature change rate and pavement width (FGSV 1995). Other official guidelines propose different design speeds according to the road functional classification and provide methods to ensure design consistency by limiting speed differences between successive design elements. This is the case of the US reference manual *A Policy on Geometric Design of Highways and Streets* (Green Book) (AASHTO 2011) and the Portuguese guidelines (JAE 1994).

The *Highway Capacity Manual* (HCM) (TRB 2010), which is regarded by practitioners worldwide as a standard reference on capacity and level-of-service procedures, also uses a segment approach to estimate the free-flow speed (FFS). First, a base free-flow speed (BFFS) based on the design speed, posted speed limit, or speeds observed in similar facilities must be adopted. Then, the FFS is estimated by reducing the BFFS for the effects of the cross-section width and density of access points. The HCM justifies that no further guidance on estimating the BFFS is provided because of the diversity of local conditions that play a major role in drivers' speed choice. However, it is possible to conclude that the BFFS is the speed observed at roads with a similar functional classification and design standards, with no access points, and lane and shoulder widths equal to or greater than 3.6 m and 1.8 m, respectively, since the proposed corrections to the BFFS are only applicable for higher densities of access points and smaller cross-section widths. The HCM only suggests the use of this method when speed measurements are not possible, e.g., at the planning and design stages of a new road, but speed estimation methods for other facilities are still required if the BFFS is established by comparison with similar roads.

The stationary observer method and the moving observer method are common procedures to assess the speed practiced at a road segment (Lum et al. 1998). In the stationary observer method, an observer placed at each end of the survey segment records the vehicles' passing times and recognition characteristics, e.g., license plates. In the moving observer method, an observer in a test vehicle chases randomly chosen sample vehicles across the segment, recording the corresponding travel times. The underlying speed concept in both methods is the space mean speed, represented by the harmonic mean of speeds over a length of roadway, which can be derived from the average travel time of vehicles to traverse the segment.

The measurement of travel times may be a time and resource consuming process. However, the use of recent technologies has alleviated travel time recording by avoiding human intervention. Studies such as Dion and Rakha (2006), Li et al. (2006), and Tam and Lam (2008) applied the principle of the stationary observer by using automatic vehicle identification (AVI) data from toll collection points to compute travel times and ultimately, speed. Jenelius and Koutsopoulos (2013) and Wang et al. (2014) applied the principle of the moving observer to assess travel times and speeds in urban links using floating car data (FCD) from probe systems installed in taxi fleets.

An alternative procedure to the stationary and moving observer methods has emerged in studies such as Rakha and Zhang (2005), Soriguera and Robusté (2011), and Martínez-Díaz and Pérez (2015), who developed methodologies to derive space mean speeds and corresponding confidence intervals from time mean speeds in freeways. The aim was to take advantage of data collected by loop detectors, which is commonly available for this type of roads. Gattis and Watts (1999) and Silvano and Bang (2016) directly associated the operating speed in small urban links to the time mean speed calculated from spot speed measurements using radar guns and loop detectors. In these studies, spot speeds are taken as being representative of the speeds practiced over a small length of roadway, which is the same principle used in many operating speed studies developed for individual curves or tangents (Passetti and Fambro 1999; Andueza 2000; Lobo et al. 2013, 2014, 2016).

In sum, the efforts to study operating speeds in road segments to date still fall behind the existing research on spot speeds. Reference manuals provide some guidance to define the design and/or operating speeds in roads of different functional classifications, but are relatively coy about explaining the underlying methods and assumptions. The academic community has developed some methods to estimate segment speeds with limited applicability, e.g., in freeways or small urban links, in an effort to simplify data collection and use data from existing road monitoring equipment.

This study presents a new segment speed prediction model, contributing to fill the gap regarding the applicability in two-lane highways. The segment speed model builds on the authors' previous research on spot speed modeling, retaining the operating speed frontier model (OSFM) formulation that allows the prediction of any user-specified percentile (Lobo et al. 2014, 2016). In the new model, the geometric and traffic characteristics are represented by a frontier function, while an asymmetric disturbance term accounts for non-quantified factors, such as the diversity in driving behavior, vehicle technology, and road environment. Segment speeds were assessed from probe vehicle data, geometric characteristics were assessed from both probe vehicle data and *in situ* measurements, and traffic effects were evaluated through the annual average daily traffic.

The segment speed model is then applicable to either an existing or planned roadway infrastructure, upon availability of the geometric design and traffic measurements or predictions. The most obvious application consists in the assessment of operational performance measures, such as travel time and cost, convenience, and efficiency. However, the model may be a helpful tool in other studies.

One potential application may regard the evaluation of design consistency using alignment indices, in line with the suggestions made by Fitzpatrick et al. (2000). The difference between the design speed and the predicted operating speed over a length of roadway is an example of what a speed-based index for consistency evaluation could be. A sensitivity analysis on such index conducted during the design stage could shed light on the variables most influencing design consistency, thus providing an insight at the most effective actions to achieve a satisfactory consistency level. Nevertheless, to improve safety performance, Fitzpatrick et al. (2000) advocates that the evaluation of design consistency using alignment indices should be complemented by a classical methodology based on speed reductions between successive elements, as proposed in studies such as Krammes et al. (1995) and Park and Saccomanno (2006).

Another potential application for the proposed model is to support the definition of speed limits. Speed limits are legislated by road functional class, but road managers may establish speed zones with different limits if the statutory limits do not comply with the specific road or traffic conditions. According to the TRB (1998), the most common approach consists in setting the speed limit near the 85th-percentile speed based on spot speed measurements at representative locations of the proposed zone. The use of the segment speed model would avoid a possible ambiguous choice of representative locations by considering the aggregated characteristics of entire zone. Following the same principle, the new model may be used to define speed zones at the design stage of a roadway infrastructure, whenever it is not feasible to adopt a design solution that fully complies with the road class's standards. Besides the traditional approach to speed limit definition, the model could be used in alternative methods such as the expert judgment (Fildes et al. 2005; NCHRP 2006; Correia and Bastos 2011) to assist experts in proposing speed limits.

The remainder of the paper is structured as follows. First, the data description details the speed collection using probe vehicles and the additional data requirements in terms of geometric and traffic characteristics. Then, the paper proceeds with the model description, presenting the OSFM formulation and the techniques used to derive the new segment speed model from a previous spot speed model presented by the authors (Lobo et al. 2016). The model estimation introduces the segment speed model for two-lane highways, calibrated for Portuguese conditions. The model validation presents the assessment of the model's validity using license plate recognition with simultaneous traffic counting at road segments beyond the calibration sample. The final section summarizes the main conclusions of this study.

Data description

To calibrate the new segment speed model, speed, road geometrics and traffic data were assessed in nine test segments contained in four Portuguese two-lane highways classified as National Roads: N14, N101, N105-2, and N206. The selected roads reflect the diversity of characteristics covered by the classification of National Roads, which represents the vast majority of the country's highway network. The design speeds vary from 40 to 60 km/h at the selected roads and the junctions are, with a few rare exceptions, at-grade intersections. Direct access to roadside properties is allowed and variables such as the lateral clearance and the density of intersections exhibit significant variations with the marginal land use. The curve radius and lane width are sometimes smaller than the minimum values recommended by the Portuguese guidelines currently in force (JAE 1994). Roads classified as Principal Itineraries or Complementary Itineraries, generically presenting higher design standards than National Roads, were not included in the present study due to data availability issues.

The test segments have between 2 and 4 km-long, and are located outside urban areas. The marginal land use varies from the complete absence of construction to the presence of some isolated buildings. The topographic features are consistent with the classification of level or rolling terrain (HCM 2010). The pavement is in good shape without cracks or potholes and with clearly visible markings. The traffic is characterized by a non-congested flow, except for the possible occurrence of isolated incidents. Segments containing signalized intersections or roundabouts were excluded from this analysis, ensuring that all the vehicles traversing the test segments have right-of-way.

Speed data was derived from probe vehicle data provided by a company specialized in digital mapping and applications. This company runs numerous probe information devices, installed onboard of professional and private vehicles, which feed a real-time traffic information system available to media partners and GPS applications. A high-rate GPS system (> 1 Hz) provides an accurate representation of each probe vehicle’s trajectory, allowing identifying the vehicles that have traversed each test segment. The space mean speed of each vehicle, consisting the model’s dependent variable, was calculated from the travel time given by the difference between GPS timestamps corresponding to the beginning and the end of the segment. To ensure a homogenous modeling sample, 75 vehicles observed in each segment in both directions were considered, corresponding to the amount of probe vehicles at the test segment with less recorded observations. In total, 675 observations were used for model estimation.

The independent variables included in the segment speed model are based on both geometric and traffic characteristics. The geometric design is characterized by the horizontal alignment, cross-section width, and density of intersections, which is in line with previous research on the speed effects produced by variables measured over a length of roadway (FGSV 1995; HA 2002; TRB 2010; Lobo et al. 2013, 2016). The horizontal alignment of the test segments was reproduced in a CAD software, using probe data collected by the instrumented vehicle of the Traffic Analysis Laboratory of the Faculty of Engineering of the University of Porto. A similar reproduction of the vertical alignment was not possible due to unreliable altimetric data. However, because of the level to rolling nature of the terrain at the test segments, the grade never surpasses a 3% value for an extension of 1 km or more, although higher grades may be present locally. According to the HCM (TRB 2010), only the segments not attaining such limited conditions must be analyzed as specific grades due to relevant speed reductions. Therefore, the lack of vertical alignment characterizing variables is not expected to represent a relevant omission in the model formulation.

Contrary to spot speed models usually dealing with free-flow vehicles, a segment speed model should account for the traffic effects. First, the practical application of this type of model to evaluate the operational performance of a roadway infrastructure, e.g., travel time and cost, and other convenience and efficiency parameters, will be more realistic if traffic conditions are considered. Second, independently from the method used to collect segment speed data, it is difficult to guarantee that sample vehicles traverse the entire segment under free-flow conditions, hence speed observations may have been affected by the presence of other vehicles on the road.

Specifically, the geometric and traffic characteristics included in the model were the bendiness (*B*), the one-direction paved width (*PW*) and its standard deviation (*SDPW*), the extra lateral clearance (*ELC*), the density of intersections (*DI*), and the annual average daily traffic (*AADT*). *B* corresponds to the sum of the deflection angles of the horizontal alignment per kilometer. *PW* represents the mean value of the lane and right shoulder combined width. The mean is calculated from measurements taken at a set of locations within the segment, spaced of around 500 m. *PW* experiments frequent variations according to the marginal land use and topography across Portuguese National Roads, especially concerning the shoulder width. Therefore, *SDPW* is included in the model to account for the effects of such diversity within a road segment. *ELC* represents the distance between the right shoulder external limit and any fixed object at the roadside. This variable is defined by the mean value corresponding to the same sites where *PW* is measured. *DI* corresponds to the number of intersections or interchanges with other public roads per kilometer. *AADT* is used as a proxy for the momentary traffic conditions faced by the test vehicles. Traffic data at the specific times and test segments at which probe vehicles were recorded was not available. Instead, *AADT* was either provided by an accident modeling study conducted at the same roads by Costa (2013) or estimated from *in situ* measurements using automatic traffic counters *VIACOUNT II*. The use of daily traffic measures as speed predictors is not new among the literature, being present in studies such as Lamm and Choueiri 1987, Jessen et al. 2001, and Schurr et al. 2002.

Because all the variables encompass a spatial dimension, reflecting either a value per unit of distance or an average value representative of the entire segment, the segment length was not included in the analysis. The minimum length of 2 km required to select a test segment ensure a reasonable distance to assess space mean speeds, as well as the necessary differentiation from spot speed studies. The statistics of the variables included in the segment speed model are shown in Table 1.

Table 1. General Data on Test Segments

Variable Description	Mean	Standard Deviation	Minimum	Maximum
Space mean speed (km/h)	49.2	9.2	21.0	80.0
B (degrees/km)	306.7	207.0	39.0	682.3
PW (m)	4.2	0.5	3.4	5.4
ELC (m)	1.2	0.4	0.7	2.2
DI (No./km)	4.0	1.8	0.5	7.0
AADT (vehicles/day)	8,736	5,545	1,750	18,135

Model description

The OSFM used in this research was introduced in previous spot speed studies by the authors (Lobo et al. 2014, 2016) to address some limitations of the widespread percentile-specific models (TRB 2011). Traditionally, the calibration of speed models is made by applying a linear regression between speed factors and a specific percentile speed obtained by the aggregation of values collected *in situ*. Besides the obvious disadvantage of providing speed estimations for one percentile only, and according to Tarris et al. (1996), the loss of information due to speed data aggregation in conventional models reduces the total variability and the nature of the variability associated to the regression function, which may bias the effects of the independent variables. Hence, modeling the entire speed distribution may contribute to rectify this problem.

The literature contains only two other models supporting a speed distribution that can be used to estimate any percentile spot speed. Figueroa Medina and Tarko (2005) employed an ordinary least squares method to estimate a customized regression equation for any intended percentile. The model is represented by a linear combination of the mean and standard deviation of the speed distribution. Hewson (2008) generalized this approach by using quantile regression.

The OSFM (Lobo et al. 2014, 2016), albeit using the entire speed distribution, follows a completely different approach based on stochastic frontier models from the econometric analysis (Aigner et al. 1977; Meeusen and van der Broeck 1977). The OSFM is formed by a deterministic speed frontier function and two disturbance terms. The speed frontier is given by an exponential function of a set of independent variables characterizing the most relevant road conditions, being estimated by the maximum likelihood method using the total number of speed observations. The exponential form represents the assumed principle according to which the effects of geometric factors are not cumulative but are dependent on the order of magnitude of practiced speeds. The values upon the speed frontier represent the upper limits of the operating speeds for each combination of independent variables; hence, the speed frontier is dubbed the maximum operating speed (*Vmax*). In other words, *Vmax* reflects the speed pattern of the most fearless drivers, which varies according to the conditions presented by the road. Then, such drivers are the most purely influenced by the road conditions and, at the same time, the least influenced by other, non-quantified factors, such as vehicle technology, driving practices, and surrounding environment. *Vmax* arises from the statistical processing of operating speed data, thus it should not be confused with speeds associated to safety limit situations affecting the vehicle's dynamic equilibrium, such as skidding and overturning.

The segment speed model is based on the authors' latest spot speed model for horizontal curves and tangents of Portuguese National Roads, introduced in Lobo et al. (2016). In this spot speed model, *Vmax* is composed by variables characterizing the local conditions, i.e., on-site geometric and visibility parameters, and variables reflecting the recent driving experience, i.e., geometric and roadside interference parameters measured over the preceding segment. The general formulation presented in Lobo et al. (2016) that supports the prediction of *Vmax* at an individual design element is given by Eq. (1).

$$Vmax_e = \exp\left(\beta_0 + \sum_{k=1}^{n_k} \beta_k \ln X_k + \sum_{m=1}^{n_m} \beta_m \ln X_m\right) \tag{1}$$

where $Vmax_e$ = maximum operating speed at a given design element; X_k = on-site characteristic k; X_m = segment characteristic m; and β = regression coefficients.

The new segment speed model is developed from the previous spot speed model, not only because both models adopt an OSFM formulation, but also because the aggregated effect produced by the segment characteristics on the operating speed is assumed identical in both models except for a scale factor. Therefore, the variable *SC,* which aggregates the segment characteristics presented in the spot speed model, such as $SC = \exp\left(\sum_{m=1}^{n_m} \beta_m \ln X_m\right)$, is used as a predictor in the segment speed model. Additionally, the new model accounts for specific effects affecting segment speeds, such as those previously mentioned in this manuscript related to the presence of traffic and the dispersion of the cross-section width. Variables characterizing individual design elements, i.e., measured locally instead over a length of roadway, are excluded from the segment speed model. Eq. (2) represents the general formulation of the model to estimate *Vmax* at a given road segment.

$$Vmax_s = \exp\left(\alpha_0 + \alpha_1 \ln SC + \sum_{q=2}^{n_q} \alpha_q \ln X_q\right) \tag{2}$$

where $Vmax_s$ = maximum operating speed at a given road segment; *SC* = variable representing the aggregated segment characteristics from the spot speed model; X_q = segment characteristic q related to traffic or the dispersion of cross-section variables; and α = regression coefficients.

Similarly to the spot speed model, the segment speed model is capable of providing any percentile speed estimation from *Vmax* by means of an asymmetric disturbance. In addition to the normally distributed disturbance (noise term) assumed in most regression models, which supports the stochastic nature of the speed frontier and represents random errors related to data collection and the model specification, the OSFM considers a second, asymmetrically distributed disturbance term that allows the estimation of speeds for drivers acting below the speed frontier *Vmax* for each combination of speed predictors. The asymmetric disturbance is suitable for representing the non-quantified speed factors related to the characteristics of vehicles, drivers, and the surrounding environment. Subsequently, the cumulative distribution function of the asymmetric disturbance allows the estimation of any percentile speed. In Lobo et al. (2014, 2016), an exponential distribution was proposed for the asymmetric disturbance, such as $f(u) = \theta \times \exp(-\theta u)$, where θ is the rate parameter of the exponential function. The cumulative function is given by $F(u) = 1 - \exp(-\theta u)$, and the inverse transform is $u = (-1/\theta) \times \ln(1 - F)$. Thus, the general form to estimate the *p*th percentile speed at a given road segment is shown in Eq. (3).

$$Vp_S = Vmax_S \times \exp\left(\frac{1}{\theta} \ln p\right) \tag{3}$$

where Vp_S = *p*th percentile speed a given road segment; and p = percentile value ($0 < p < 1$).

The OSFM is estimated using the maximum likelihood method, which is more efficient in managing asymmetric disturbances than the least squares estimator (Greene 2008). The best parameter estimation is obtained by maximizing the log-likelihood function represented in Eq. (4).

$$\ln L = N\ln\theta + \frac{N}{2}\theta^2\sigma_v^2 + \theta\sum_{j=1}^{n_j}\sum_{i=1}^{n_i}\left(v_{ij} - u_{ij}\right) + \sum_{j=1}^{n_j}\sum_{i=1}^{n_i}\ln\Phi\left(-\frac{v_{ij} - u_{ij}}{\sigma_v} - \theta\sigma_v\right) \quad (4)$$

where L = likelihood function; N = total number of observations; σ_v = standard deviation of the noise term distribution; v_{ij} = noise term for vehicle i in segment j; u_{ij} = asymmetric disturbance for vehicle i in segment j; and $\Phi(.)$ = standard normal distribution function.

Model estimation

The calibration of the new segment speed model for Portuguese conditions was performed through a stochastic frontier regression between the space mean speeds of all sample vehicles and the road geometrics and traffic based on Eq. (5), which represents a linearized form of Eq. (3) and details the model formulation with the previously described variables.

$$\ln Vp_s = \alpha_0 + \alpha_1 \ln SC + \alpha_2 \ln SDPW + \alpha_3 \ln AADT + \frac{1}{\theta}\ln p \quad (5)$$

where $SC = PW^{0.079} \times ELC^{0.008} \times B^{-0.027} \times DI^{-0.036}$. To comply with the OSFM formulation, the speed predictors were previously transformed in log terms, which implies that the model is not applicable when *ELC, B, DI*, or *SWPD* are null.

Model estimations were made with the help of the econometric software Limdep (Greene 2007), using the maximum likelihood method. The regression modeling results are shown in Table 2.

Table 2. Results of the Stochastic Frontier Regression

Variable	Coefficient	Standard Error
Constant	4.846	0.197 [a]
ln *SC*	4.462	0.437 [a]
ln *SDPW*	-0.125	0.019 [a]
ln *AADT*	-0.064	0.019 [a]

Note: Log-likelihood = 143.617; number of observations = 675; σ_u = 0.168; σ_v = 0.124; θ = 5.947.
[a]Significant at 1% level.

These results translate into the final specification for the model to estimate Vmax and the *p*th percentile speed in segments of Portuguese National Roads represented by Eqs. (6) and (7).

$$\begin{aligned} Vmax_S &= \exp(4.846 + 4.462 \times \ln(PW^{0.079} \times ELC^{0.008} \times B^{-0.027} \times DI^{-0.036}) - \\ &\quad - 0.125 \times \ln SDPW - 0.064 \times \ln AADT) \end{aligned} \tag{6}$$

$$Vp_S = Vmax_S \times \exp\left(\frac{1}{5.947} \times \ln p\right) \tag{7}$$

with *ELC*, *B*, *DI*, and *SWPD* > 0.

The model functional form allows the interpretation of the coefficients of the individual variables as elasticities. The geometric variables, particularly those related to the cross-section width, represent the most relevant effects affecting operating speeds. An increase in *PW* while keeping the remaining variables constant produces a positive impact on speed, materialized by an elasticity of 0.352. The impact of increasing *ELC* is also positive, albeit with a smaller elasticity of 0.036. Additionally, the negative coefficient of *SDPW* reflects that the variation of *PW* over a road segment has a negative impact on speed. Many Portuguese National Roads are characterized by a non-constant paved width, mainly attributed to frequently changing shoulder widths according to the marginal land use, which introduces uncertainty in drivers' expectations about the road ahead, leading them to adopt a more cautious speed choice. The speed impacts caused by increases in the density of intersections and bendiness are negative, with elasticities of -0.161 and -0.120, respectively. The results also show that, as expected, increasing traffic leads to speed reductions. Particularly, the elasticity associated to *AADT* denotes that a traffic increase of 10% under a non-congested flow would produce a decrease in the space mean speed of 0.6%.

Model validation

The segment speed model was validated using two 3-km-long road segments, S1 and S2, belonging to two Portuguese National Roads not included in the modeling sample, N 108 and N 222, respectively. Both roads have differentiated characteristics; the former is much older than the latter, which translates into lower standards in terms of horizontal curvature, cross-section width and roadside interference. The traffic in S1 is lower than is S2 because the former is located farther away from a major urban center. Table 3 contains the characteristics collected for both validation segments.

Table 3. Geometric and Traffic Characteristics of the Validation Segments

Variable	S1	S2
B (degrees/km)	199.3	63.5
PW (m)	4.4	6.6
ELC (m)	1.4	1.0
DI (No./km)	4.3	3.0
AADT (vehicles/day)	6,193	15,290

The validation procedure was aimed at testing if the model specification supports reliable segment speed predictions, particularly as far as the use of *AADT* as a proxy for the momentary traffic conditions is concerned. Therefore, percentile speeds obtained from the model and from measurements conducted at the validation segments were compared against each other for equivalent traffic flows. The comparison was made for peak and daytime off-peak traffic conditions. The nighttime off-peak period was not analyzed because it is assumed that the traffic flow is low enough to ensure free-flow conditions for almost all the vehicles.

The validation procedure started with the implementation of 24-hour traffic measurements to characterize the peak and daytime off-peak traffic flows at each segment in a labor day. An automatic traffic counter *VIACOUNT II* was placed approximately at the midpoint of each segment. The highest half-hourly traffic volume was observed during the afternoon peak in both segments, specifically between 5:45 and 6:15 PM in S1 and between 6:00 and 6:30 PM in S2. The daytime off-peak conditions were associated to the lowest half-hourly volume observed between the morning and the afternoon traffic peaks, which occurred from 4:45 to 5:15 PM in S1 and from 4:15 to 4:45 PM in S2. The half-hourly basis was selected to contain the use of resources in the following step, conducted at the equivalent time periods of another labor day. In that step, an observer recording the vehicles' license plates and passing times, and an automatic traffic counter for reliable traffic measurements were placed at both ends of each validation segment. The license plate recognition allowed to derive segment percentile speeds from *in situ* observations (Vp_{so}) for peak and daytime off-peak traffic periods. In turn, the simultaneous traffic measurements allowed obtaining segment percentile speed estimations from the model (Vp_{se}). Because the model uses *AADT* as an explanatory variable, the half-hourly traffic volumes observed at peak or daytime off-peak periods were converted to a daily basis by multiplying for 48. This transformation led to Vp_{se} estimations corresponding to hypothetical situations of constant traffic flow during 24 hours. Although such situations are unrealistic, this procedure ensures that Vp_{se} and Vp_{so} report to similar traffic flows.

The comparison between Vp_{se} and Vp_{so} was performed through the 15th-, 50th-, and 85th-percentiles (*V15*, *V50*, and *V85*), which are the most commonly used in speed modeling applications. To better guide this comparison, the random error component was applied to speed estimations in the form of an interval defined around Vp_{se} by the standard deviation of the noise term distribution, such as the limits of the interval are given by $Vp_{se} \times \exp(\pm\sigma_v)$. The results are plotted in Fig. 1 and 2, corresponding to peak and daytime off-peak traffic flows, respectively.

For peak traffic conditions, the observed percentile speeds lie within the interval defined by the standard deviation of the noise term in four out of six cases, with the V85 estimations sitting 1 km/h above and 2 km/h below the interval for S1 and S2, respectively. For daytime off-peak traffic conditions, the observed values are also contained in the interval in four out of six cases. The observed V15 and V85 in S1 surpass the upper limit of the interval by 4 and 2 km/h, respectively.

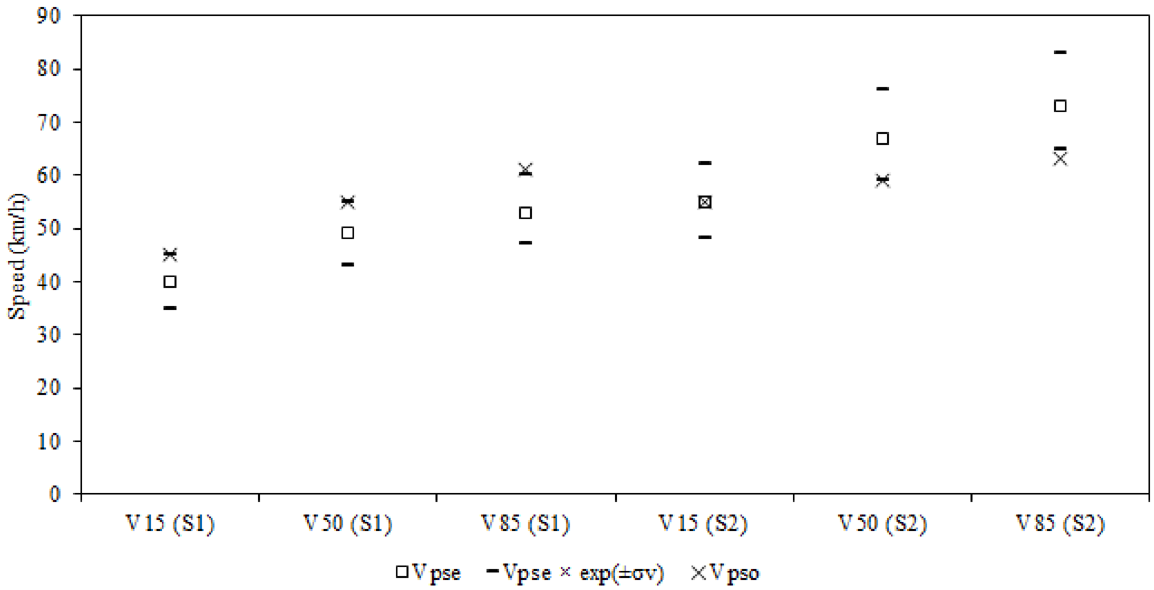

Fig. 1. Validation results for peak traffic flow

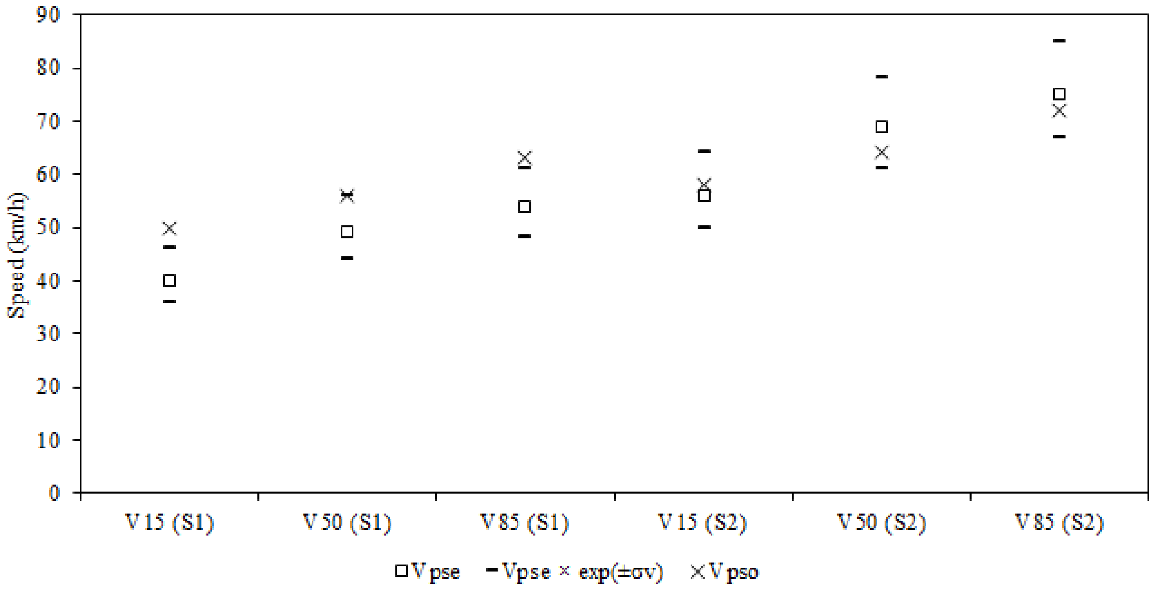

Fig. 2. Validation results for daytime off-peak traffic flow

These results may denote a slight underestimation of the segment percentile speeds by the model in National Roads with lower design standards, with half of the observed values presented for S1 being placed above the corresponding intervals. The model performs better in the case of S2, representing a National Road with a higher design speed, with just one of the observed percentile speeds falling below the interval for a small margin. The segment speed model also seems to return more accurate predictions for medium-to-small percentiles.

However, from a global perspective, the observed percentile speeds are contained by the interval around the estimated values in eight out of twelve cases. In the remaining four cases, speed deviations from the corresponding intervals are, at most, of 4 km/h. Therefore, the selected speed predictors, including *AADT*, does not seem to affect the validity of the segment speed model, which has revealed the capability to support reliable speed estimations under different geometric and traffic conditions.

Conclusions

Speed is one of the most important factors affecting the convenience and efficiency of roadway infrastructures. Drivers' perception of the operating speeds of different routes and, consequently, of travel times and costs strongly influences route choice. Likewise, road designers and managers use the operating speed to evaluate and monitor the performance of infrastructures in terms of safety, traffic flow and environmental efficiency.

Notwithstanding the notable contribution of numerous spot speed models existing in the literature to enhance speed-prediction capabilities, the road performance evaluation can be significantly improved through the development of segment speed methods. The estimation of operating speeds over a length of roadway is usually associated to the measurement of the corresponding travel times, which can be very time and resource consuming, especially if no automatic data collection is involved. In practice, such difficulties have been hampering the development of new segment speed prediction tools; the existing ones are mostly limited to freeway and urban links, taking advantage of data collected by monitoring equipment owned by road authorities and concessionaires.

The objective of this study was to develop a model to predict operating speeds in segments of two-lane highways. The new model retains the OSFM formulation from the authors' previous spot speed models (Lobo et al. 2014, 2016), which confers the ability to estimate any user-specified percentile speed. A deterministic speed frontier representing the maximum operating speed was established as a function of the road geometrics and traffic. The asymmetric disturbance term, accounting for non-quantified factors, such as diversity in driving behavior, vehicle technology, and road environment, allows the estimation of percentile speeds through its cumulative distribution function.

The segment speed model was calibrated using the entire speed distribution from a probe vehicle database, corresponding to nine test segments belonging to Portuguese National Roads. Because simultaneous speed and traffic data was not available for the test segments, *AADT* was used as a proxy for the momentary traffic conditions faced by the sample drivers. The model estimation results confirm the primary influence of geometric characteristics on the speeds practiced under non-congested traffic conditions; the impact of traffic is much smaller and predictably negative.

Model validation was made using license plate recognition in two additional road segments, each one presenting differentiated geometric and traffic characteristics. This procedure allowed obtaining simultaneous speed and traffic data, which was used to assess percentile speeds from both *in situ* measurements and model estimations. The model has proved reliable in its predictions, with the observed speed values lying within or sufficiently close to the interval around the estimated values defined by the standard deviation of the noise term distribution. It should be noted that the model was calibrated for the road conditions observed in Portugal, thus its application in a different context should be carefully considered, especially in non-European countries where geometric standards may vary significantly. However, the model formulation is sufficiently versatile to be replicated by practitioners across the globe for a broad range of road conditions.

With this study, the authors achieved the goal to evolve their research from spot speed (Lobo et al. 2013, 2014, 2016) to segment speed modeling, by delivering the only model applicable to segments of two-lane highways to date that was developed outside the scope of official guidelines, with the major advantage of supporting estimations of any percentile speed. Therefore, the model significantly enhances the capabilities to predict the operating speed over a length of roadway, representing a relevant contribution to future road performance and safety applications, such as the evaluation travel times, the recommendation of efficient routes, the definition of speed limits, or the analysis of design consistency.

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8

CONCLUSIONS

The improvement of operating speed models is essential to assist an increasing number of applications in road monitoring and management and to further consolidate the role of operating speed in the design process, as a means to involve driver expectancy in the definition and control of geometric parameters. This thesis has addressed vital aspects of operating speed modeling for enhancing speed prediction capabilities in two-lane rural highways. The work herein covers the identification of the most relevant limitations of the existing operating speed models and the development of new models with innovative features and increased applicability, calibrated for Portuguese roads. This involved a data-driven approach, including an extensive collection of vehicle speeds and of several parameters representing road geometry and roadside interference. The key findings and contributions of this thesis and the guidelines for future research are provided in subsequent sections.

8.1. KEY FINDINGS

The most relevant findings of this research are described as follows:

- The conditions for the occurrence of vehicle platooning depend on the impacts that local road characteristics produce on general driving behavior. In the case of Portuguese two-lane highways, a minimum time gap of 6 s between successive vehicles is suitable to represent free-flow traveling conditions.

- The driving simulator study shows that the effect produced by the simultaneous variation of lane and shoulder width do not correspond to the sum of the same effects taken individually. Therefore, this interaction should be considered in operating speed studies.

- All the spot speed models developed for Portuguese two-lane rural highways show a primary influence of the horizontal alignment on the operating speed, and smaller speed effects produced by the cross-section and the vertical alignment. These findings are in line with the previous studies on the operating speed of passenger cars.

- The recent driving experience and the expectations about the road ahead also play a role in drivers' speed choice. In fact, the characteristics of the upstream segment and the visibility to downstream were found impacting spot speeds, albeit to a lesser extent than on-site geometrics;

- On-site and upstream variables seem to have a greater impact on the spot speeds practiced in National Roads than in Principal and Complementary Itineraries. This may denote that more restrictive and less homogeneous designs generically presented by roads of the former category may induce some additional caution in drivers' speed choice. On the contrary, a severe limitation of the sight distance affects more the driving speeds in Principal and Complementary Itineraries, where such situation is less common and potentially unexpected.

- For non-congested traffic conditions, the traffic shows a smaller impact on segment speeds in comparison to road characteristics.

- The use of large samples in model development is crucial to estimate the speed impacts of a wide array of variables.

- The OSFM is a powerful tool to account for the variability in speed distribution explained by factors that are not easily measureable, such as the diversity in driving behavior and vehicle technology. The model's asymmetric disturbance proves itself as a suitable representation of these effects, which, in this way, directly intervene in the estimation of percentile speeds.

8.2. CONTRIBUTIONS

This thesis delivers the contributions summarized below:

- Suggestion of an approach to test for free-flow traveling conditions, considering the diversity in driving behavior that may occur as a reflection of road geometry. This approach, used in this study for Portuguese roads, may be replicated in other countries or regions to assist further developments in speed modeling.

- Introduction of the OSFM formulation. This modeling approach introduces the concept of maximum operating speed, i.e., the speed of the fastest driver estimated for each combination of road characteristics, from which it is possible to derive any user-specified percentile speed. The flexibility of percentile speed estimation is representative of the potential of the new models to assist diverse applications in road design and management. Additionally, the OSMF formulation is sufficiently versatile to be replicated by practitioners across the globe for a broad range of road conditions.

- Development of other distinctive features to improve the specification of operating speed models, namely: (i) the use of exponential functions to account for the interaction between the explanatory variables and the order of magnitude of speed, (b) the consideration of on-site, upstream and downstream effects in spot speed estimations, and (c) the consideration of traffic effects in segment speed estimations.

- Proposal of four new mathematical expressions to predict percentile spot speeds in Portuguese two-lane highways, specifically in curves and tangents of National Roads, Complementary, and Principal Itineraries.

- Proposal of a segment speed model for Portuguese National Roads. In addition to the advantages inherent to the OSFM formulation, this model can be particularly relevant for practitioners, because of the following reasons: (i) segment speed predictions can contribute to a preliminary/macroscopic analysis of design consistency (ii) there is an increasing number of applications related to road management and routing that use segment speeds, and (iii) only a few segment speed prediction tools exist in the literature, all of which are proposed by official guidelines with limited transferability to different contexts.

8.3. GUIDELINES FOR FUTURE RESEARCH

In continuation of the work done so far in this thesis, the proposed model formulations can serve as a basis for future operating speed studies, following the guidelines descried below:

- Consider additional effects to enlarge the models' scope of applicability, particularly regarding the study of operating speeds during the nighttime or under adverse weather conditions.
- Develop further efforts to understand speed variations across a specific design element, as a means to improve the representation of speed profiles for safety evaluation. This can be achieved by modeling speeds at different points of the element and eventually by evaluating acceleration and deceleration rates.
- Enlarge the range of calibration of the segment speed model with the inclusion of additional segments of National Roads and extend the scope of applicability to Principal and Complementary Itineraries.
- Model the operating speed of heavy vehicles.

It is foreseeable that technology will play an increasing role in operating speed studies in the near future, particularly through data gathered by an increasing number of devices installed on-board vehicles. Additionally, as the automotive industry moves toward automation, it is expected a major paradigm shift for road design and operations management. This will create an opportunity for researchers to rethink about the most adequate speed concepts to tackle the challenges of the road system's transition to a new era.