

SPEED MANAGEMENT IN RURAL TWO-WAY ROADS – SPEED LIMIT DEFINITION THROUGH EXPERT-BASED SYSTEM

Nuno Gregório
Ana Bastos Silva
Álvaro Seco
University of Coimbra

1. INTRODUCTION

Speed is one of the most relevant factors that characterize road operation, directly and decisively influencing its evaluation by all its users, having several effects, either positive or negative. Usually, the most perceptible effect of speed is its impact over road accidents, whether over occurrence risk or over severity, whose relationship has been demonstrated by several studies (Baruya, 1998; Farmer et al., 1999; Kloeden et al., 2001; Taylor et al., 2002; Nilsson, 2004; Aarts & van Schagen, 2006; Elvik, 2013). Speed also affects environmental conditions, namely in what concerns exhaust emissions, fuel consumption, noise and the quality of life for people living and working near the road (ERSO, 2006; Kockelman, 2006; Austroads, 2010).

Despite the widespread use and acceptance of speed limits throughout the world, no consensus has so far been achieved among practitioners relating to the most adequate methods and techniques to be used to select the appropriate speed limit in a given road section. This is a major concern, since it leaves the technical personnel without definitive guidance in this field (Forbes et al., 2012).

Furthermore, the ever growing urban developments in most roads surrounding areas has, in many countries, led to the existence of not only purely rural environments, but also disperse and non-consolidated built-up areas in their surroundings, with the boundaries between these zones very often difficult to identify. This has resulted in ever more complex road environments, where the traditional road design and management principles tended not to be sufficient, with the subsequent problems arising to speed management strategies and, as a result, to speed limit setting methods, in terms of coherence and homogeneity (Aarts & van Schagen, 2006; Hauer, 2009; Stuster et al., 1998).

Hence, the major objective of the current work is to provide an integrated decision-support methodology for speed limit setting in interurban single-carriageway roads, crossing different types of road environments with a mixed use, capable of taking into consideration a range of significant and objective variables.

A number of approaches have over the years been developed and adopted to set speed limits in interurban roads. Most of these methodologies usually give prevalence to geometric features of the road layout, both in their vertical and horizontal alignments, and especially in critical sections, such as curves,

intersections or in stretches with higher slopes. Examples of this approach can be found in numerous studies and are usually the basis of official guidelines and statutory documents. However, given the complexity inherent to the road environment, a wider set of factors related to the surrounding areas, safety, traffic and users may need to be included. A robust methodology should consider the wider number of factors possible, weighting their significance in this process.

The current work aimed to deliver an accessible and easy to use by the technical community methodology, based on data which can be collected remotely and is easily measurable. Therefore, a different approach is considered, which emphasizes factors related with the prevailing road environment, especially focusing on road integration into the surrounding areas. Previous work has already been done to develop a robust methodological approach (Seco et al., 2008; Correia & Bastos Silva, 2010; Correia & Bastos Silva, 2011; Bastos Silva et al., 2012). However, additional development is still necessary regarding the following subjects: 1) Use of an expedite method of expert assessment in laboratory; 2) Development of a new database, involving more itineraries crossing different environments, and thus broadening the model's applicability and representativeness; 3) Overall improvement of the methodological approach.

2. LITERATURE REVIEW

Currently, four major approaches are adopted by the scientific and technical community to set speed limits: engineering philosophy, economic optimization philosophy, harm minimization philosophy and expert-based systems.

2.1. Engineering philosophy

According to this philosophy, speed limits are usually set based on an analysis of traffic and the road environment on the section under study and its surrounding roads. This approach includes as main basic methodology the Operating Speed Method, which has been widely used throughout the world, but especially in the United States, with notable examples in several states (such as Illinois, for instance) (Forbes et al., 2012).

The Operating Speed Method is based on the 85th percentile of speed (V85) and its usual procedure includes setting the speed limit in a value equal to or higher than the V85, eventually adjusting it in accordance to specific infrastructure and traffic conditions (Forbes et al., 2012). It takes into account that speed values equal to or near a standard deviation over the mean value (which is near that percentile) tend to correspond to a minimum accident risk for the driver (DfT, 2013). It also takes into consideration that this kind of speed limit is in accordance to the perception of a vast majority of users about which is the adequate speed under specific traffic conditions, thus contributing to a more uniform speed regime (FHWA, 2009; Forbes et al., 2012).

Nevertheless, this method presents several disadvantages: it unrealistically assumes that drivers select their travel speed taking adequate and objective consideration of road safety issues; it is considered to be the cause of a gradual increase of the average operating speed; it produces an inadequate measure of speed consistency; it tends to be less effective the more residential the surrounding environment is; and it cannot be considered as objectively rational, since it considers an erroneous driver perception of speed impacts (Elvik, 2010; Park & Saccomanno, 2006; TRB, 1998).

2.2. Expert-based systems

The philosophy centred on expert-based systems is related with the previous methodology, intending to answer to its lack of consistency and uniformity, and aiming at more realistic results (Austroads, 2005). These systems are computational based programs which are used to solve complex problems recurring to decision algorithms and a database, allowing it to simulate the behaviour and the reasoning, evaluation and decision process of experts (MnDoT, 2012). Among all the components that compound such a system, the database – knowledge base – is particularly relevant, since the system bases its decisions on it. This database includes information arising from the experts' knowledge and experience, structured in tasks to execute and decisions to take (TRB, 1998).

The development of the model that establishes the relationship between the knowledge base and factors shall be carried out by collecting information in a set of representative cases. The calibration of this model uses the speed limit values previously devolved by the experts, establishing the knowledge base. After the definition of the model function, the system is prepared to estimate the speed limit value, based on data related to each one of the considered factors.

In general, the advantages of using this type of approaches are evidenced by practice, which shows its comprehensiveness, consistence and reliability, as well as the fact of being easily reproducible in different contexts (Forbes et al., 2012). This type of systems has been widely applied in several places in the last few decades, with Australia (XLIMITS family programs) and USA (USLIMITS) as the most representative cases.

2.3. Harm minimization philosophy

The Harm Minimization Philosophy addresses the speed limit setting problem on a road safety perspective, considering that it is against ethics to allow situations where there is a possibility of accident occurrence. It, thus, focus on the tolerance and integrity of the human body in accident situations to set the speed limit. It has been implemented in some countries, with Sweden (Vision Zero) and the Netherlands (Sustainable Safety) as the most representative cases.

Vision Zero takes into account three fundamental ethical imperatives: no individual can die or suffer chronic injuries as a consequence of accident; road safety cannot be considered as a mobility function, but rather as a road safety function; a monetary value or cost can never be attributed or associated to human life (Vaa, 1999). Furthermore, this approach also usually forgives the driver in case of accident, since even the systematic non-observance of the established rules by the users supposes their inadequacy (Whitelegg & Haq, 2006). However, the activity of particularly vulnerable users is not appropriately addressed (Vaa, 1999), and its realism and rationality are also questioned (Elvik, 1999; Rosencrantz et al., 2007).

The Sustainable Safety approach also considers that it is not ethically acceptable for a system to allow frequent accident occurrence with fatal or serious injuries (Vaa, 1999), aiming to create a road system in which accident occurrence is strictly limited by an intrinsically safe road environment. Thus, speed limit setting must allow to influence both traffic homogeneity, and road layout and user behaviour predictability, and must be safe and credible (Wegman & Aarts, 2006). Lack of credibility from the driver's perspective may lead them to question and ignore it, and, thus, need to be avoided (Goldenbeld & van Schagen, 2007).

2.4. Economic optimization philosophy

Unlike the previous approach, the Economic Optimization Philosophy intends to attribute a monetary value to all costs related to mobility, including those which are due to accident-caused damage. Among the various available methods, the Optimum Speed Limits approach has been the most disseminated and used.

The Optimum Speed Limits methodology was initially proposed by Oppenlander (1962), and intends to regulate traffic speed from a general society's point of view, recognizing that individual users not always select speed taking account of the risk imposed over the other road user individuals. This is due to the non-consideration by the traditional methods of the external costs associated with mobility, namely those arising from fuel consumption, emissions, noise and accidents, constituting a market imperfection (Elvik, 2010). Therefore, curves of the cost function associated to each one of these factors must be developed to the various road sections, under different traffic conditions. The optimal speed value must be fixed as the minimum point of the total function, corresponding to the minimum transport cost from the society's point of view.

Elvik (2002) modelled the optimal speed limit based on four different perspectives – society, road user, tax payer and local resident –, emphasizing that the process is restricted by the capacity of including all relevant costs, as well as by the reliability and validity of the methods used to determine their monetary value. The question of costs estimation is also discussed in Delhay

(2006), which addresses accident-related costs; Tarko (2009), involving safety, time and enforcement issues, through the analysis of the subsequent trade-offs; and Flügel et al. (2015), which analyses the utility of a road safety-related attribute, involving the number of casualties per year.

Despite the partially antagonistic visions of these philosophies, all approaches present important contributions. Harm Minimization and Economic Optimization philosophies are each focused in a very specific subject, thus, in some cases biased results may be a consequence of not considering other factors. Data reliability is another limitation of the latter strategy. Engineering philosophy is effective and accessible, although it is too dependent on a single factor (V85) and often produce incoherent, inconsistent and non-uniform results. The expert-based approach is a relevant improvement of this latter strategy, producing more realistic results, involving more easily available data and embracing a wider number of factors, but it has so far been applied mostly in Australia and USA, without any known European case until now.

3. METHODOLOGICAL APPROACH

This study aimed to develop a decision-support methodology to set speed limits in two-way roads, based on a limited set of explanatory variables related to road environment and surrounding areas. The supporting model considered 3 possible choices for the dependent variable (i.e., the speed limit value): 50 km/h, 70 km/h and 90 km/h. The developed system is an expert-based one, following the previously presented assumptions, and based on previous experience (Seco et al., 2008; Correia & Bastos Silva, 2010; Correia & Bastos Silva, 2011; Bastos Silva et al., 2012).

3.1. Expert and site selection

A number of 4 experts, selected based on their experience and expertise in the field (experts in traffic safety and traffic engineering academics), intervened in two main phases: they analysed the final set of variables to include in the model; then, they independently attributed a speed limit value to each analysed road stretch, based on an evaluation only influenced by road functionalities and interaction with the surrounding environment.

A number of 4 road itineraries was selected, corresponding to road segments of interurban highways, in which data collection was carried out. These itineraries were representative of several characteristic situations of two-way roads – on the one hand, these roads crossed several types of environment, namely urban areas, transition zones and rural environments; on the other hand, these roads did not present too irregular or heterogeneous layouts, so that these factors did not prevail over the remaining during the speed limit setting process. Moreover, some of these itineraries were selected in regions with disperse population, and other ones in regions with a more concentrated and consolidated urban pattern.

3.2. Basic data collection process

The process of data collection was carried out in successive 200 meters road stretches, in which each itinerary was divided. This length was considered to be a sufficiently short length to guaranty a homogeneous level of both road physical features and surrounding environment characteristics. Simultaneously, this distance was also considered to be long enough to enable experts to make stable and conclusive assessments.

Data related with each one of the explanatory variables (see Table 1) was, whenever possible, collected through examination of satellite/aerial imagery, like Google Earth and similar supports, and by using an instrumented vehicle. In cases in which this was not possible, or data was not reliable, information was collected through direct observation *in situ*.

3.3. Experts' data collection

Experts chose their speed limit proposals among three alternatives, each one corresponding to one of the three road environments considered in this study: 50 km/h (31 mph), the statutory speed limit for urban roads in Portugal; 70 km/h (43.5 mph), which is considered an adequate value for transition zones, with disperse urban occupancy; and 90 km/h (56 mph), the statutory speed limit for rural highways in Portugal, which was also adopted as the reference alternative in the modelling process. The second most restrictive speed limit value of those chosen by each expert was selected for each road stretch, in order to develop a model representative of conservative assessments, while at the same time making the model results more stable by reducing the impact of lack of consensus between experts.

Experts assisted in laboratory to video recorded in each of the itineraries, in both directions, which allowed these trials to happen on homogeneous and replicable conditions, due to its more controlled environment and to the fact that each expert always analyses each road in exactly the same conditions of the other experts (avoiding the influence of undesirable factors to this process, such as weather conditions). Laboratorial conditions also allow the expert to avoid the sense of continuity between two successive stretches. However, an analysis carried out *in situ* would always involve a higher degree of realism and would allow a higher degree of autonomy by experts, which would have implications over their behaviour.

Those assumptions, as well as the suitability and realism of the laboratory trials, were assessed in a test in which an expert analysed the same road in both situations: *in situ* and in laboratory. The obtained results showed a high degree of consistence between the speed limit values delivered by both scenarios, with an overall error of only about 1.05%, meaning that in almost every stretch the expert delivered the same speed limit value. It is also worth mentioning that the majority of stretches where divergence between results occurred are situated

in transition zones. A t-test, a parametric statistical test, was carried out. A p-value of 0.175 was obtained, which implies that the null hypothesis of the test is not rejected for the usual level of significance (95%), meaning that the mean values of both samples are significantly closer, in statistical terms. Thus, it is possible to conclude that both scenarios present significantly similar results and that the laboratorial environment can appropriately substitute an *in situ* assessment.

3.4. Multinomial Logit model

The system's function, which establishes the relationship between the knowledge base and the included factors, can be estimated by several models. In this specific case, it is considered that speed limit setting is, essentially, a discrete choice problem. Discrete choice models are based on the theory of stochastic utility, in which the choice is carried out by the user aiming to maximize the utility function. The utility function is composed as a combination of known explanatory variables, the systematic part of the utility, and its random part, which is unknown (Ben-Akiva & Lerman, 1985). Thus, this function has the following form:

$$U_{in} = V_{in} + \varepsilon_{in} \quad (1)$$

where U_{in} represents the utility function, given by decision-maker n to alternative i , V_{in} its systematic part and ε_{in} the error between the systematic part and the true utility. The systematic part of the utility function given by user n to alternative i is, in its turn, represented by the following expression:

$$V_{in} = \beta_{0i} + \beta' X_{in} \quad (2)$$

where β_{0i} is the specific constant of each alternative i , β' represents the vector of weights and X_{in} is a vector of attribute values for each alternative i , given by a decision-maker n . The error between the systematic part of the utility and its true value can be regarded as the random part of the utility.

The Multinomial Logit model, which is part of this family, is based on the assumption that the error terms of the alternatives are all independent and identically distributed (IID), according to a Gumbel distribution (Ben-Akiva & Bierlaire, 1999), implying that any difference between the error terms is logistically distributed. Thus, the probability of choice of alternative i in this model is the following (Ben-Akiva & Lerman, 1985):

$$P_n(i) = P(U_{in} \geq U_{jn}) = \frac{e^{V_{in}}}{\sum_{j \in C_n} e^{V_{jn}}} \quad (3)$$

where C_n is the choice set. The best method to estimate this model is through maximum likelihood, using the following function, in its linear form:

$$L = \sum_{n=1}^N \sum_{i \in C_n} y_{in} \log(P_n(i)_n) \quad (4)$$

where y_{in} represents the binary variable which assumes value 1 if the decision-maker n chooses alternative i , and 0 otherwise. The IID of the error term hypothesis and its distribution imply the Independence of Irrelevant Alternatives (IIA) assumption, which states that the ratio of two alternatives is independent from the choice set (Ben-Akiva & Bierlaire, 1999).

3.5. Explanatory variables

The set of variables was selected based on TRB (1998), Greibe et al. (1999), Fitzpatrick et al. (2001), Lu et al. (2003), Austroads (2005), Cruzado & Donnell (2010), and DfT (2013), and is presented in Table 1.

TABLE 1 – Explanatory variables (R at the end of the variable name for nearside variables and L for offside ones. Portugal is a country with right-hand traffic.)

	NAME IN MODEL	DESCRIPTION	TYPE
1	INTERR	Intersections at the Nearside(NS)	Discrete
2	INTERL	Intersections at the Offside (OS)	Discrete
3	GARAGR	Off-Road Individual Parking Accesses at the NS	Discrete
4	GARAGL	Off-Road Individual Parking Accesses at the OS	Discrete
5	NATERR	Motorized Traffic Lateral Accesses at the NS	Discrete
6	NATERL	Motorized Traffic Lateral Accesses at the OS	Discrete
7	NAPARR	On-Road Parking spaces at the NS	Discrete
8	NAPARL	On-Road Parking spaces at the OS	Discrete
9	NAPEDR	Pedestrian Paths' Accesses at the NS	Discrete
10	NAPEDL	Pedestrian Paths' Accesses at the OS	Discrete
11	NAPEHR	Buildings' Pedestrian Accesses at the NS	Discrete
12	NAPEHL	Buildings' Pedestrian Accesses at the OS	Discrete
13	NBUSR	BUS Stop at the NS	Discrete
14	NBUSL	BUS Stop at the OS	Discrete
15	NCRO	Formal Pedestrian Crossings	Discrete
16	NGASR	Filling Station at the NS	Discrete
17	NGASL	Filling Station at the OS	Discrete
18	SIGNR	Speed Control Traffic Lights at the NS	Discrete
19	SIGNL	Speed Control Traffic Lights at the OS	Discrete
20	SIDEWR	Sidewalks at the NS	Binary
21	SIDEWL	Sidewalks at the OS	Binary
22	ISLAND	Central Island	Binary
23	AVCOR	Medium Level of Lateral Restrictions at the NS	Binary
24	AVCOL	Medium Level of Lateral Restrictions at the OS	Binary
25	HICOR	High Level of Lateral Restrictions at the NS	Binary
26	HICOL	High Level of Lateral Restrictions at the OS	Binary

However, variables involving accident data, the prevailing operating speed regime and the traffic volume were not included, due to being difficult to collect this data and, also, to assure that the final model can be easily used by the

technical community, which would also have problems to obtain this information.

Variables with a binary character represent the existence (value 1) or non-existence (value 0) of the feature. Likewise, discrete variables represent the number of elements of that type which can be found along the stretch in analysis. The levels of lateral restrictions have a binary character, since they imply associating each stretch to one of the two situations (one representing moderate level of lateral restrictions, and another one of high levels). This level of lateral restrictions expresses the influence of the road immediate surrounding environment and, above all, of its most prominent elements. Every variable, excepting NCRO and ISLAND, are independently determined for both sides of the road.

4. MODEL RESULTS

A MNL model was developed, in the way described above. The number of statistical cases corresponds to 2216 cases (277 stretches x 2 ways x 4 experts). The correlation matrix analysis has shown no significant correlations between the different explanatory variables (above 0.8, according to Hensher (1994)), which led to all variables being maintained in the developed model in the initial modeling stages. Those variables with a significance lower than 5% were then gradually excluded from the model, in order to increase its robustness. The final specification for both non-reference alternatives is presented in Table 2. The SPSS application was used.

A McFadden pseudo- R^2 of 0.413 was obtained, which, according to Domencich & MacFadden (1975), corresponds to a R^2 of around 0.70 – 0.80. This is a very high value, considering its usual range, indicating an adequate goodness of fit and a strong predictive capability. Moreover, this model presented a high level of consistence, since almost all the coefficients of the explanatory variables share the same sign (positive). It is also worth noting that these coefficients have generally higher values in 50 km/h alternative than in 70 km/h, which is consistent with the fact that 90 km/h, a closer value to 70 km/h, was selected as the reference alternative. In fact, it is expected that an increase in explanatory variables values causes a higher difference between the utilities of the lowest speed limit and the reference one.

Variables related with the presence of sidewalks (SIDEWL) – those with the highest coefficients for 50 km/h –, presence of intersections (INTERR) and lateral accesses (NATERL), as expected due to the fact that these elements are particularly characteristic of built-up environments, proved to have a much higher weight over 50 km/h utility. On the other hand, the presence of formal pedestrian crossings (NCRO) – the highest coefficient for this alternative –, of bus stops on the near side (NBUSR) and of speed-control traffic lights (TLIGH) are only significant for 70 km/h, which is not an intuitive result for transition

zones. In fact, these variables are not applied in the analysed sites with objective criteria, which may be the cause of this non-expected outcome.

TABLE 2 – Calibrated coefficients for the MNL model.

50km/h (31 mph) utility coefficients					70km/h (43.5 mph) utility coefficients				
MCFADDEN PSEUDO R ² =0.413									
Variable	β	Std. Error	Exp(β)	Sig.	Variable	β	Std. Error	Exp(β)	Sig.
50Intercept	-5.127	0.416		0	70intercept	-1.542	0.163		0
INTERR	1.500	0.347	4.483	0	INTERR	1.216	0.263	3.374	0
INTERL	1.016	0.350	2.763	0.004	INTERL	0.907	0.262	2.477	0.001
GARAGR	0.875	0.221	2.399	0	GARAGR	0.754	0.210	2.126	0
NATERL	0.836	0.193	2.307	0	NATERL	0.550	0.163	1.733	0.001
SIDEWR	3.547	0.780	34.718	0	SIDEWR	(Not significant thus not included)			
SIDEWL	3.463	0.757	31.927	0	SIDEWL	1.330	0.654	3.782	0.042
NBUSL	1.738	0.727	5.683	0.017	NCRO	2.077	0.577	7.978	0
AVCOR	2.287	0.479	9.840	0	NBUSR	1.016	0.354	2.761	0.004
AVCOL	1.637	0.478	5.140	0.001	TLIGHR	1.076	0.369	2.932	0.004
HICOR	2.072	0.428	7.941	0	AVCOR	1.748	0	5.743	0
HICOL	2.883	0.424	17.868	0	AVCOL	2.012	0	7.481	0

The presence of bus stops (NBUS) on each side proved significant in only a single alternative (in 50 km/h for the opposite side, in 70 km/h for the near one), which was probably due to the fact that there is a relatively high correlation between these variables, above 0.5, indicating that they could probably be aggregated in a single explanatory variable without losing much information (in fact, bus stops are usually placed opposite to each other, in both sides of the road). Unsurprisingly, the subjective variables for lateral restrictions (AVCO, HICO) are among those with the highest weights in both alternatives, although those corresponding to a high level (HICO) are not significant for 70 km/h.

Finally, and also as expected, there is a tendency for a stronger and more frequent integration of variables representing the nearside of the road traffic flow, indicating that, despite taking into consideration the characteristics of both sides of the surrounding environment, experts tend to value the nearside over the offside.

5. CONCLUSION

This work aimed to deliver an accessible and easy to use methodology to set speed limits in rural two-way roads. Thus, an expert-based system was developed, involving the knowledge base composition through the collection of expert assessment results on a number of rural roads, as well as several explanatory variables characterising the road environment and its surrounding areas. Special attention was given to these two elements and its influence over

speed limit setting, disregarding the more traditionally used factors related with road geometry and layout. The relationship between speed limits and these variables was estimated through a Multinomial Logit model, using, as much as possible, data collected by examination of satellite/aerial imagery and the use of an instrumented vehicle.

In order to deliver their speed limit proposals for each analysed road stretch, experts assisted in laboratory to video information, instead of carrying out their assessment *in situ*, allowing a higher level of homogeneity and replicability of the method. This approach was validated through a testing trial, where it showed a high degree of consistence and its adequacy to be used instead of an *in situ* based assessment.

Model development was defined through the selection for each road stretch of the second most conservative evaluation made by 4 different experts. The obtained results proved to be consistent and robust. The estimated model presented a McFadden pseudo- R^2 of 0.413, which is a high value, denoting a strong predictive capacity.

Nevertheless, some further development and validation of these models is still needed. More specifically, other explanatory variables, capable of a more objective classification of road environment and surrounding areas typology, ought to be identified. This identification must be supported by a careful evaluation of the expert assessment in what it is less well fulfilled by the model output. Other speed limit levels should also be considered as available alternatives to expert's assessment, since they will eventually enable a more realistic and accurate modelling process. The overall model should be simplified in what some not so objective variables are concerned.

Other speed limit setting approaches should also be developed in order to incorporate a cost-benefit perspective, including aspects related to accidents, pollution, energy consumption or travel time costs, besides the already considered safety and user behaviour aspects.

Finally, further work ought to be developed to define a methodology capable of supporting the definition of speed management strategies throughout extended lengths of routes, along which it is essential to guaranty consistent and smooth speed limit profiles, in accordance with driver expectancies.

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