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[RW1 – 1] APPLICATION OF FUZZY TECHNIQUES FOR DETERMINING THE OPERATING SPEED BASED ON ROAD GEOMETRY

ABSTRACT

The operating speed is certainly one of the most important variables in the management of road safety. Its determination has been refined in the last few years by means of experimental analyses that have also sanctioned its strong link with the context in which speed surveys are carried out. In fact, even though all the algorithms proposed have a very simple analytical structure, it has been noted that they can never have a general character and thus be applied without losing a certain amount of reliability.

Moreover, the technological development today achieved would allow for recording in a complete way of the road environment as modern measuring instruments provide in digital format and in an economically convenient manner a great amount of data.

As such, the aim of this work is to propose a methodology that allows not only the ordering and classification of numerous important data but one that is able to recognise the presence of links of dependence between unknown variables a-priori or, in any case, of difficult analytical characterisation. The technique of clustering used in order to achieve this is preliminary to the organisation of a general fuzzy model that takes into account certain variables of input linked to the geometry of the road and to the visibility and that provides as output the operating speed.

Such model has been applied to a rural road located in Messina (Italy) and the results achieved, tested with experimental surveys as well as with algorithms present in literature, are very encouraging and invite deeper exploration of the study.

KEY WORDS

operating speed, fuzzy logic, road safety, accident, visibility, [RW1 – 2] road geometry

1. INTRODUCTION

The ultimate aim of road designing is to ensure the movement of vehicles and people in a short space of time and in the safest possible way. Therefore, the ideal is to plan a road with geometric and constructive characteristics that meet the expectations of the users so as to diminish driving errors. Scientific production in the last 25 years with regard to this has been impressive and in this paragraph a short synthesis will be traced in order to assess the main results achieved and to identify the contribution that this can provide to the subject in question. Among the first researchers, Alexander and Lunenfeld [1] have distinguished the driver's expectation during the distance covered into two well defined classes: the first, named "a priori", is based on the experience of driving acquired during our own life; the second, called "ad hoc", is strongly influenced by the surrounding environment. Not being able to influence the experience and the driving ability, the authors have deepened the study of this latter aspect.

Historically, Lamm and his collaborators [2, 3, 4, 5, 6] were among the most eminent authors in this field, not only for having created the three criteria based on the determination of the design and operating speed, on the friction and the relationships that are formed between them, but, rather, because they have applied them in many contexts, assessing their effectiveness. With regard to the correlation between bendiness and operating speed, McLean [7] analyzed the influence of the stretch of road on human behaviour and elaborated a model used in the standards of many countries. He introduced the concept of speed environment V_{env}, that is the maximum speed which the driver would maintain with regard to the surrounding environment, in conditions of free flow, in the absence of elements of restriction and uniquely according to the risk perceived by road environment.

Because of the complexity of the road system, the equations that define the phenomenon observed are all of empirical origin, inferred, in a few words, by regression analyses more or less evolved according to the number and the type of variables included in the problem. With regard to this, Gibreel et al. [8] organized the sector literature, classifying the existing methodologies according to speed measurements, performance and safety. Among noteworthy research Nicholson [9] can be cited, who identified in the design speed and in the superelevation two indices for the control of homogeneity, and also Gattis & Watts [10] for their studies in urban environment accompanied by a rigorous analysis of accidents.

It must be said that almost all authors have agreed in identifying in the lack of homogeneity the cause of diffused accidents [11, 12, 13]. The power of computers, enormously increased during the last few years, has been used to extend bidimensional analysis with more realistic analyses in 3D [14]. Moreover, with regard to this, Hassan et al. [15, 16] have pointed out the need to have an evolved procedure in the control of road designs, also enriching their own algorithms with the measurements of operating speed, stability of the vehicle and workload.

The skill of new generation equipment, able to collect a huge quantity of data referring to several variables, has led to the need for a rational procedure that has allowed optimisation of the problem through the choice of an appropriately linked function objective [17, 18]. All the existing procedures in literature have the character of strong contextualization, that is, they can be applied only in very similar environments with regard to those in which they have been obtained [19]. This explains the great number of published algorithms, all equipped with very good tests of significance but which, unfortunately, lose some validity when the road context changes only slightly.

Some authors [20, 21] have distinguished themselves not only for the immense and accurate experiments in an urban and rural ambit, but also for having found a data set of remarkable dimension, arranged by means of techniques of data mining, in order to identify further links between the variables at stake. For the first time the requirement is felt to classify the solid data base found and, above all, relationships are found between unknown variables a priori without resorting to traditional statistical techniques, rather useless for these purposes.

Similar models have been published by Choueri et al. [22] for Lebanon, Islam and Seneviratne [23] for the United Kingdom, Bird and Hashim [24], Hassan et al. [25] and Crisman et al. [26].

Some studies carried out with the aid of driving simulators are also interesting, as they have allowed the monitoring of a greater number of variables in much faster times [27, 28, 29].

The last few years have actually witnessed the exploration of various techniques different from the usual ones, preferably linked to artificial intelligence. Along this line, for example, the research of Taylor et al. [30] has been developed: they have proposed a forecast model of the operating speed within road works based on neural networks and dependent on variables such as horizontal and vertical geometry, cross section and traffic.

More recently, Cruzado & Donnell [31] have deepened detailed topics, addressing the problem of the homogeneity of speeds when passing from one uninterrupted flow area to a mainly urbanized area.

However, the scientific community agrees in holding that the assessment of homogeneity is not simple, especially if of new designing, as it would be necessary to refer to algorithms whose choice depends on the similarity between the environmental context in which they have been obtained and that scenario in which they will be applied.

2. BASIC HYPOTHESIS

As has been verified from this short synthesis, the need has been developed to equip oneself with a forecast instrument that takes into account numerous variables that can manage a database of important dimensions and that increases its own reliability according to future surveys and updates. The answer can come from the use of techniques of soft computing, such as fuzzy logic, neural networks, genetic algorithms. Of course, the fuzzy approach is not always preferable to other methods. It produces more realistic results when the number of the variables involved is significant and, above all, when their dependency would make other techniques impossible to apply [32, 33].

In fact, the treatment of the uncertainties in probabilistic terms is correct when the system is constituted by components whose reliability in a determined temporal period has been measured and verified and whose variability is contained in sufficiently limited contexts [34]. Unfortunately, when the human component intervenes, as in the case of road safety, the sample is strongly inhomogeneous and presents such high variability as to produce rather inexact final results [35, 36].

The aim of the present work is, therefore, the predisposition of a forecast instrument that allows the determination of the V85, i.e. the speed exceeded only by 15% of the users in certain standardized conditions [4, 37], according to certain variables considered significant and present within the road context and, in particular, also those connected to the aspect of “visibility”. It is believed that the model so constructed has importance as it also allows the analysis of homogeneity in roads of new design, with environmental contexts that can be adapted through the quantification of appropriate variables of reference. Moreover, its application to interventions of adaptation on the existing roads allows the assessment of the relationship between the V85 and the conditions of safety more effectively as the criticalities present referring to problems of visibility are recognized.

In this phase of the study, the membership functions and the rules that feed the fuzzy model have been calibrated through techniques of fuzzy clustering applied to data of a preset survey on an existing road. Therefore, such procedure would have to totally eliminate the strongly subjective approach generally reproached in analyses of this kind.

In the course of the experimentation the proposed model revealed itself to be much effective for the analysis of the relationships existing between the V85 and the aspects connected to the visibility of the road. However, the authors hold that for the design of the existing road, the predictive models of the V85, in general terms, must allow an analysis in this direction. And, indeed, still more complete models can be formulated by introducing further variables.

3. SURVEY OF METHODS

The forecast of the variable V85 through the predisposition of a fuzzy model fuzzy requires a series of phases referable to the identification of input data and to the definition of the membership functions and of the fuzzy rules. Lastly, the final results must be compared with reference values in order to be able to provide a judgment on that carried out and, above all, to identify the unavoidable elements of weakness in order to be able to subsequently resolve them.

As such, the procedure followed by the authors has been subdivided into the following steps:

a) Acquisition of the geometric characteristics of the road to be examined.
b) Determination of the Sight Distance offered by the road, of that demanded by Italian standard and of the design speed.
c) Recording of the speeds of vehicles on 18 cross sections located in correspondence to the centre of the curves and calculation of the V85.
d) Arrangement of a fuzzy model fed by the data relative to only 14 sections. On the remaining 4, predictive analysis will be used.
e) On all 18 sections a law of regression for the calculation of V85 will be applied obtained for Greece [4] that has demonstrated greater adaptability to the study context, so as to have a further element of comparison in order to judge the correctness of the fuzzy model.

a) Geometric characteristics of the road

The study was conducted on a 22km stretch of a rural road called “SS 113” that connects Messina with Trapani (Italy). The infrastructure is old, antecedent to modern road standards and, as such, is composed of a succession of straight stretches and circular curves, without the presence of elements of transition.

The alignment is very winding, with short straight stretches interposed between the curves. The variability of the radii of the horizontal curves is greatly elevated and spans from a minimum of 24 metres to a maximum of 3,300 metres. The longitudinal slope is modest for the entire development (0% ≤ i ≤ 3%). Moreover, the road is characterised by low volumes of traffic, absence of intersections and private access in the nearby areas and by sufficient geometric homogeneity so as not to induce abrupt manoeuvres by users.

The main geometric characteristics were found by the authors through examination of digital cartography in 3D and with the aid of a differential GPS.

b) Sight Distances and design speed

The Sight Distances effectively available (AVD) were obtained using the commercial software (Civil Design® by Digicorp), through the preparatory reconstruction of horizontal and vertical alignment of the road, including identification of all the obstacles in three dimensions of the space able to influence the driver’s vision. The 3D analysis, as is well-known, is more precise than the traditional 2D analysis, as it allows consideration of the effective course of the vision radius according to the altimetry of the road and of the obstruction of the obstacles with their effective heights.

The calculation of the stopping sight distance, as required by Italian standard (ISSD), is carried out by means of the resolution of the equation below, substantially similar to that contained in many international standards:

$$D_A = D_1 + D_2 = \frac{V_0}{3.6} \cdot \tau - \frac{1}{3.6^2} \cdot \int_{V_0}^{V_1} \frac{V}{g \cdot \left[f_1(V) \pm \frac{i}{100} \right] + \frac{R_a(V)}{m} + r_0(V)} dV \qquad (1)$$

where the variables contained in the expression have the following meaning:

- D_1 = distance covered over time τ (m);
- D_2 = braking distance (m);
- V_0 = design speed of the vehicle at the beginning of braking, equal to the design speed obtained punctually from the design speed diagram (km/h);
- V_1 = final design speed of the vehicle, in which $V_1 = 0$ in case of stopping (km/h);
- i = longitudinal slope of road (%);
- τ = total reaction time (perception, reflection, reaction and performance) (s). Italian standard recommends setting this variable equal to $2.8 - 0.01 \times V_0$;
- g = gravitational acceleration (m/s^2), equal to 9.8 m/s^2;

m = mass of the vehicle (kg). Italian standard recommends setting this variable equal to 1,250 kg;

R_a = aerodynamic resistance (N). Italian standard recommends setting this variable equal to $(2.61 \times 10^{-5} \times V_0^2)$ × m;

f_l = longitudinal coefficient for braking. Italian standard recommends inferring this variable from literature;

r_0 = unitary resistance to rolling, negligible (N/kg).

The two sight distances will constitute variables of input for the fuzzy model.

Knowledge of the geometry of the road has also allowed for valuation of the design speed *Vd*, obtained according to the indications provided by the Italian standard, in a way greatly similar to that which takes place with the standard of other countries. In the case in question, it is not important to report the course of the Vd on the whole map but on the curves. The speed on these elements can be obtained from the following expression, that links the radius *R* (m), the inferred design speed *Vd* (km/h), the coefficient of lateral friction (function of the *Vd*) and the cross-sectional slope of road *q* (%):

$$Vd = \sqrt{127 \times R \times (f_t + q)} \quad (2)$$

c) V85 determination

The campaign of the survey was carried out during daylight hours, with dry and regular paving and good meteorological conditions. Of course, according to the procedure for this type of measurement [2, 3, 4, 5, 6], the conditioning factors due to traffic were not considered, nor did motorcycles, commercial or heavy vehicles, or cars with spacing between them of a time interval less than 5 seconds take part in the analysis.

The speed was surveyed by means of a laser speed gun. This instrument, as is known, measures the round-trip time for light to reach a vehicle and reflect back and shoots a very short burst of infrared laser light and then waits for it to reflect off the vehicle.

For every place, the speeds of over 250 vehicles were recorded, obtaining from the analysis a minimal number not lower than 100 isolated vehicles. In total, more than 9,000 passages were therefore acquired and all the data collected was processed in order to obtain the 85th percentile of the values of the speeds (V85). The analysis, as already stated, is based on the study of 18 sections in curve, out of which 14 are used for the creation of the fuzzy model fuzzy and 4 for its verification.

For each of the 18 sections analysed, the main parameters of interest were assessed in order to reconstruct the distribution of the speeds and, therefore, the determination of the V85.

The density of relative frequency f_i of the class was calculated with the well known equation:

$$f_i = \frac{n_i}{n \cdot A} \quad (3)$$

From the relative frequency, this then passes to the cumulated frequency through equation:

$$F_i = A \cdot \sum f_i \quad (4)$$

meant as the frequency to which the vehicles travel at the lower speed or equal to the speed considered. In this way it was possible to reconstruct the course of the distributions of the frequency in relation to the position of each section.

Referring to the equations reported above:

n_i = the absolute frequency, that is the number of elements pertaining to the class;

n = the total number of the elements in the series of data;

A = the amplitude of the class.

The information thus collected allowed the reconstruction of the distributions of the frequency in relation to the position of each section and the calculation of the representative value of the 85th percentile.

d) The fuzzy model

The prearrangement of the predictive model necessitated the development of certain preliminary steps. First of all, the identification of the variables involved in the phenomenon and the characterization of their uncertainty constitute a passage of fundamental importance.

The choice to represent the variables with the fuzzy logic allows the use of natural language through the judgments of the experts, the achievement of flexibility in the model, tolerance to inexact data and the possibility of representing non-linear functions of arbitrary complexity.

In this regard, a membership function MF or μA(x) is a function that defines how each point of X in the input space is mapped to a membership value (or degree of membership) between 0 and 1. Fuzzy operators represent the verbs of fuzzy logic and the “if-then-else” rule statements are used to determine all the conditional definitions. The if-part of the rule is called the antecedent, while the then-else part of the rule is called the consequent.

[RW2 – 3] In general, the rules have the form:

If x is A then y is B.

where ‘x is A’ is the antecedent part and ‘y is B’ is the consequent; x and y are defined as fuzzy sets (or reference fuzzy sets) on domains $X \subset R^n$ and $Y \subset R^m$, respectively. A and B can be constant linguistic terms as ‘low temperature’, ‘good compaction’, etc.

Very often, when the analyst wants to enhance the level of precision of the model, it is necessary to define different terms Ai on the domain of one variable and the collection of these fuzzy sets $[A_1, A_2, \ldots, A_m]$ is called a fuzzy partition. The number of linguistic terms in the partition is called granularity of the model.

A and B are in many cases multidimensional fuzzy sets and generally, for a simpler use, the antecedent conditions are usually defined in an univariate and decomposed form and are composed by logical operators like "and" (conjunction) and "or" (disjunction) as:

If x_1 is A_1 and ... and x_m is A_m then...

Since in practical applications it is necessary to have final crisp values, the procedure has to provide for fuzzification and defuzzification steps.

Usually, the most famous procedure is called fuzzy-mean defuzzification and it is applied to the centroids (means) of fuzzy sets B_i:

$$b_i = \frac{\sum_{q=1}^{N_q} \mu_{B_i}(y_q) \cdot y_q}{\sum_{q=1}^{N_q} \mu_{B_i}(y_q)} \quad \text{with } i = 1, 2, \ldots, N \tag{5}$$

where N_q is a number of discretization levels.

The crisp output of the fuzzy model y_0 is, instead, calculated as the weighted mean of b_i:

$$y_0 = \frac{\sum_{i=1}^{N} \mu_i \cdot b_i}{\sum_{i=1}^{N} \mu_i} \tag{6}$$

The output is deducted as a weighted average of the rule contributions:

$$y = \frac{\sum_{i=1}^{c} \mu_{A_i}(x) \cdot y_i}{\sum_{i=1}^{c} \mu_{A_i}(x)} \tag{7}$$

where c is the number of rules and μ_{A_i} is the membership degree of the i-th rule antecedent.

In this paper reference is made to fuzzy modelling of Mamdani-type [38], that was built to control a steam engine by means of a set of linguistic control rules, based on Zadeh's studies on fuzzy algorithms for complex systems and decision processes. This method expects the output membership functions to be fuzzy sets. After the aggregation step, there is a fuzzy set for each output variable that has to be defuzzificated. It is more convenient to use a single spike as the output membership function (singleton output) rather than a distributed fuzzy set and so it can be thought of as a pre-defuzzified fuzzy set [39]. It can be synthesized by means of the following steps:

- Evaluate the antecedent for each rule: given the inputs (crisp values) it is possible to obtain their membership values. This process is called "input fuzzification". If the antecedent of the rule has more than one part, a fuzzy operator (t-norm or t-conorm) is applied to obtain a single membership value.
- Obtain each rule's conclusion: given the consequent of each rule (a fuzzy set) and the antecedent value obtained in step a), a fuzzy implication operator must be applied to obtain a new fuzzy set. Generally, two of the most commonly used implication methods are the minimum, which truncates the consequent's membership function, and the product, which scales it.
- Aggregate conclusions: in this step the outputs obtained for each rule in step b) are combined into a single fuzzy set, using a fuzzy aggregation operator, as the maximum, the sum or the probabilistic sum.
- Defuzzification: in a decision problem, the output must be a number (crisp value) and not a fuzzy set. So, the fuzzy set must be transformed into a single numerical value with defuzzification methods such as the centroid one, which returns the centre of the area under the fuzzy set obtained in step c).

Generally, fuzzy models can present some criticism with regard to the definition of membership functions and rules that link the dependencies between the variables involved because of the excessive subjective contribution by the analyst. [RW 2 – 1] In fact, a variable is represented by means of some membership functions whose number, shape, interval of validity is generally managed by the analyst. This one will affect with their subjectivity also the relations between the variables that in a fuzzy model are indicated by the rules.

For example, in the case in which the analyst would classify within their model small radii and large radii should identify two representative values of these two conditions. But this depends strongly on the characteristics of the road examined (R = 150m can be considered small for a rural road and large for a local road) and, however, would not solve the membership assignment to one or the other function of all the other radii. Finally, should it be decided what other variables are affected by this parameter, it is extremely subjective to report these relations inside some rules.

This problem can be resolved through recourse to procedures of clustering, applying them to data of relief that will therefore be interpreted, organized and classified in an appropriate way [40, 41]. In fact, these methods are used to identify experimental groupings of data from a large data set to produce a synthetic representation of a system's behaviour by means of optimal membership functions.

More in particular, the techniques of clustering, as in this case, are used as preprocessors in order to determine the fuzzy rules fuzzy if-then and the membership functions. For example, the one called Subtractive Clustering is an algorithm that calculates the number and the centre of clusters in a data set. This technique [42] uses the data points as candidates at the centre of the clusters, making computation proportional to the size of the problem. Since every point can represent the centre of the cluster, a measurement of density for every point x_i can be determined through the following expression:

$$D_i = \sum_{j=1}^{n} \exp\left[-\frac{\| x_i - x_j \|^2}{(r_a/2)}\right] \quad (8)$$

where r_a is a positive constant that represents surrounding radius.

Therefore, a data point will have high value of density if it has many points close by. The first centre of cluster x_{c1} is chosen as the point that has the greatest value of density D_{c1}. Therefore, the measurement of density or of potential of every data point x_i is calculated as:

$$D_i = D_i - D_{c1} \cdot \exp\left[\frac{\| x_i - x_j \|^2}{(r_b/2)^2}\right] \quad (9)$$

where r_b is a surrounding radius, therefore we will have a meaningful reduction of density (or of the potential) and generally this is equal to 1.5 r_a in order to avoid having centres too close to each other.

The process continues until a criterion of stop is reached [43].

In case of small radii, there will be many clusters and, therefore, a greater number of membership functions and rules. Further rules, beyond those inferable from the process of clustering, can be added so as to better calibrate the relationships between the variables involved.

The model proposed here is composed of the following six variables of input:

1. Radius of the curve [m];
2. Development of the curve [m];
3. CCRs [gon/Km];
4. Design speed [Km/h];
5. Sight Distance available [m];
6. Stopping Sight Distance required by Italian standard [m].

In the application carried out in this article, the road has no transition curves. Only in this case, R is directly correlated to the CCR and one of these variables loses significance. However, their presence is essential to the general fuzzy model, as it can be applied to roads that have the presence of transition curves.

The unique variable of output is V85 [Km/h].

e) Models of literature for the calculation of V85

As previously stated, the equations present in literature were applied to the road in question for the calculation of V85. The algorithm that provided the best correlation (R^{2*}) with the experimental data was that contained in Lamm et al. [4] and contextualised for Greece, reported here below:

$$V85 = \frac{10^6}{(10150.1 + 8.529 \cdot CCRs)} \quad (10)$$

where, as well known, the *CCRs* (Change Rate of the single curve) are equal to:

$$CCRs = 63700 \cdot \frac{\left(\frac{L_1}{2 \cdot R} + \frac{L_2}{R} + \frac{L_3}{2 \cdot R}\right)}{L} \quad (11)$$

The symbols contained in the aforementioned expressions have the following meaning:

- R [m] – radius of the circular curve;
- L_1 and L_3 [m] – length of the transition curves (precedent or successive with regard to the circular curve); in the road examined these lengths are equal to zero;
- L_2 [m] – length of the circular curve;
- L [km] – total length of the curve.

The coefficient of determination, applied to the data observed, is:

$$R^{2*} = 1 - \frac{\sum (V85 - V85_{ext})^2}{\sum (V85 - \overline{V85})^2} \quad (12)$$

where:

- $V85$ – the data observed;
- $V85_{ext}$ – the data estimated by the regression model;
- $\overline{V85}$ – their average.

For the sake of brevity the results obtained with the application of other empirical models present in literature will not be reported, as they are less reliable than those reported in equation (10).

4. RESEARCH RESULTS

The survey and subsequent elaboration of the equations contained in the previous paragraph have allowed reconstruction of the geometry of the road examined, the design speed and the Sight Distances. The final results are summarized in *Table 1*.

As result of the surveys of speed, for every section the main statistical parameters were calculated that have allowed obtaining of the value of V85 in several sections. Also in this case, for reasons of brevity, only the case of section 18 is reported (*Table 2*).

V85 of 18 sections obtained in this way is reported in *Table 3*.

The application of the techniques of subtractive clustering allowed the measurement of the membership functions and the rules. [RW3 – 3] The simulation has been performed with the Matlab® software and in particular, the procedure followed allowed the identification of the two functions for each of the six variables of input, all of Bell type and, therefore, characterised by three parameters, indicated here as a, b and c (*Table 4*). For the sake of brevity, in Figures 1 and 2 only the functions relative to the variables of input Radius and CCRs are reported. [RW2 – 4] All other figures can be built by the values contained in *Table 4*.

Table 1 – Report of the input variables along the 18 bends of the road. The rows in bold have been tested with the fuzzy model.

Bend n°	Radius [m]	Length [m]	CCRs [gon/Km]	Vd [Km/h]	AVD [m]	ISSD [m]
1	200.00	89.29	318.50	72.43	44.80	90.94
2	700.00	79.47	91.00	100.00	209.31	155.27
3	220.00	97.98	289.55	76.29	96.97	98.58
4	80.00	133.77	796.25	50.88	29.38	54.71
5	500.00	86.25	127.40	100.00	86.17	155.27
6	800.00	159.95	79.63	100.00	80.01	155.27
7	**350.00**	**161.90**	**182.00**	**91.63**	**55.75**	**133.16**
8	110.00	126.28	579.09	57.91	66.13	65.42
9	45.00	110.80	1,415.56	40.06	19.94	40.00
10	**80.00**	**84.20**	**796.25**	**50.88**	**32.60**	**54.69**
11	37.00	69.33	1,721.62	36.86	70.42	36.02
12	**60.00**	**60.54**	**1,061.67**	**45.19**	**49.21**	**51.70**
13	38.00	48.05	1,676.32	37.28	21.86	36.54
14	55.00	53.15	1,158.18	43.58	20.74	44.56
15	**45.00**	**54.67**	**1,415.56**	**40.06**	**23.97**	**40.00**
16	100.00	35.84	637.00	55.72	32.81	61.98
17	130.00	104.10	490.00	61.92	72.62	71.99
18	200.00	42.73	318.50	73.47	66.85	92.96

Table 2 – Main statistical characteristics of the variable speed in Bend No. 18.

Average	57.7
Median	56.84
Mode	55.102
Standard dev.	10.392
Kurtosis	-0.371
Minimum	31.765
Maximum	78.261
Interval	46.496

[RW3 – 1] It should be noted that the number of membership functions depends on the number of clustering chosen to classify the data from the data set. Of course, the greater the number of clusters and, therefore, the number of membership function, the smaller the dispersion of the observations. However, this will be a very complex fuzzy model and its interpretation is made more difficult, especially when the number of observations is quite limited.

Moreover, the technique of clustering allowed identification of the dependencies between the variables

Table 3 –V85 determined by means of the trials

Bend No.	$V85_{exp}$
1	70.80
2	65.64
3	67.92
4	58.06
5	90.00
6	75.00
7	85.71
8	72.00
9	52.17
10	61.02
11	50.00
12	42.86
13	52.94
14	46.15
15	46.15
16	76.60
17	68.32
18	68.35

Table 4 – Parameters of the input membership functions

	Radius		Length of Bend		CCRs		Vd		AVD		ISSD	
	MF1	MF2	MF1	MF2	MF1	MF2	MF1	MF2	MF1	MF2	MF1	MF2
a	381.5	381.5	62.06	62.06	821	821	31.57	31.57	94.68	94.68	64.65	64.65
b	2	2	2	2	2	2	2	2	2	2	2	2
c	37	800	35.84	159.9	79.63	1,722	36.86	100	19.94	209.3	-54.04	75.26

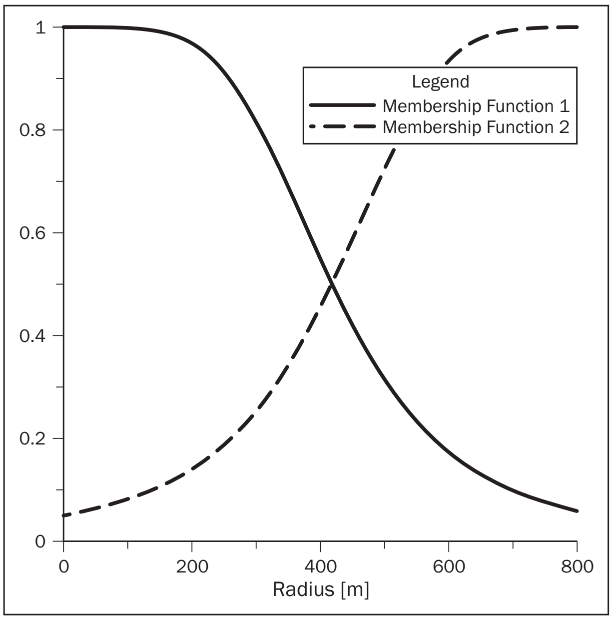

Figure 1 – Input variable Radius for the fuzzy model

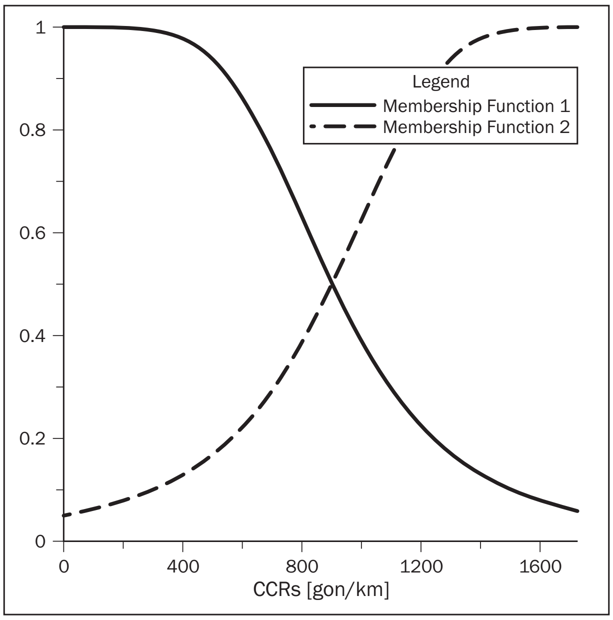

Figure 2 – Input variable CCRs for the fuzzy model

of input and the transfer of these to the fuzzy model through the explicitness of the rules. In the case under consideration 64 rules were obtained; here below an extract is reported, having indicated with inxmfy the variable of input x (with x= 1,..., 6) referred to the membership function y (with y= 1, 2) and outmfz the variable of output referred to the membership function z (with y= 1, 2,..., 64):

1. If (Radius is in1mf1) and (Bend_Length is in2mf1) and (CCRs is in3mf1) and (Vd is in4mf1) and (AVD is in5mf1) and (ISSD is in6mf1) then (V85 is out-1mf1).
2. If (Radius is in1mf1) and (Bend_Length is in2mf1) and (CCRs is in3mf1) and (Vd is in4mf1) and (AVD is in5mf1) and (ISSD is in6mf2) then (V85 is out-1mf2).
3. If (Radius is in1mf1) and (Bend_Length is in2mf1) and (CCRs is in3mf1) and (Vd is in4mf1) and (AVD is in5mf2) and (ISSD is in6mf1) then (V85 is out-1mf3).
4. ...
5. If (Radius is in1mf2) and (Bend_Length is in2mf2) and (CCRs is in3mf2) and (Vd is in4mf2) and (AVD is in5mf2) and (ISSD is in6mf2) then (V85 is out-1mf64).

[RW2 – 5] From Figures 1 and 2 and *Table 4*, it can be noted that the membership functions were assigned names very far from the usual lexical language used by humans (in1mf1 or in6mf2 rather than small, medium, high, etc.) to highlight the role played by the clustering techniques used in the previous phase of the analysis to grant greater objectivity to the entire procedure. [RW2 – 6] [RW3 - 2] [NEW RW] Each rule produces a consequent, through a specific fuzzy operation (AND or OR) and a suitable method of implication (MIN in this case).

Subsequently, all the consequents will be aggregated into a single function and the crisp output value will be extracted by the method of the centroid.

Table 5 reports the values of V85 of sections 7, 10, 12 and 15 so as to be able to compare the operation of the fuzzy model ($V85_{Fuzzy}$) regarding the experiment ($V85_{exp}$) or to one of the algorithms ($V85_{Greece}$) more reliable present in literature (7).

Table 5 – Comparison among the speed deduced during the trials, with the regression formulated for Greece and by means of the fuzzy model proposed

Bend No.	R [m]	$V85_{exp}$	$V85_{Greece}$	$V85_{Fuzzy}$
7	350	72.00	85.50	70.50
10	80	58.35	59.00	55.90
12	60	57.14	52.10	47.90
15	45	52.94	45.00	47.20

The coefficient of determination, applied to the data observed, is sufficiently satisfactory and is equal to:

$$R^{2*} = 1 - \frac{\sum (V85 - V85_{ext})^2}{\sum (V85 - \overline{V85})^2} = 0.75 \qquad (13)$$

5. DISCUSSION

Modern instruments of survey (video cameras, GPS, speed camera, etc.), characterized by exit signals of digital type, produce databases of large sizes according to the frequency of sampling set up by the operator. Generally, such frequency tends to increase in order to improve the precision of the relief, but this leads unavoidably to having a great amount of information that must be ordered and opportunely classified in order to be truly useful to the analyst. Furthermore, modern techniques of clustering, such as subtractive clustering used here, allow the recognition of links between the variables monitored not always known a priori or, in any case, classifiable with difficulty, for obvious analytical difficulties, with the usual techniques for the management of uncertainties.

The proposed model is extremely flexible and, as such, it applies well both to the introduction of new variables of input that can be inserted in order to complete knowledge of the examined environmental context as well as to the increment of the dimension of the existing sample already identified. Both aspects, even though they increase the task of the survey and computation in the preliminary stage, should lead to more reliable results.

Thanks to this preliminary procedure, the proposed model has overcome one of the notorious weak points of the fuzzy logic, that is, the definition in objective terms of the membership functions and of the rules, at first entrusted only to the sensitivity of the analyst.

In order to assess the correctness and the usefulness of the model, it is necessary to examine the meaning of the results obtained also in relation to how much is inferable with the present algorithms in literature (*Table 5*).

In the first curve (R = 350m) an optimal adaptation of the fuzzy model can be noted (70.50km/h) to the surveys carried out (72.00km/h), while the law of regression (Lamm et al., 1999) moves away from both values (85.50km/h); in the second curve (R = 80m), all three results are sufficiently homogenous, with difference in the results less than 5km/h.

The third curve (R = 60km/h), instead, presents homogenous results only between survey (57.14km/h) and the algorithm of Lamm et al. [4] (52.07km/h), while the fuzzy model is decidedly distanced (47.90km/h). The reason for such discrepancy could be due to the fact that, in this curve, the distance requested by the Italian standard is similar to that which is effectively offered by the road. Therefore, the greater completeness of the fuzzy model (which takes into account user's visibility), in this case, does not improve the reliability of the response because the visibility is not a critical element of the scenario. Rather, the structure of fuzzy model would be complemented by other variables that can identify more precisely the speed.

In the last section of control (R = 45m), the fuzzy model produced a more faithful answer (47.20km/h) regarding the survey (52.94km/h) with regard to what was made by the model of Lamm (45.00km/h).

Further considerations can be deduced. The differences recorded between $V85_{exp}$, that is, that effectively recorded and that calculated with the mode l of Lamm are minimal only in the case of bend No. 10 (-1.11%). In particular, curve 7 presents a very high $V85_{Greece}$ (18.75%), probably as it does not take into account the effective visibility available, very far from that required by stopping. In curve 15, the difference between the two $V85$ is contained in module (about 8km/h) but it is elevated in percentage (15%) but this time the visibility available is not very distant from that required. In the other two curves the difference of speed between the two methods is inferior to 10% and it is considered that such a difference is acceptable and, in any case, due to other variables not taken into account in the model of Lamm which is extremely simplified.

Similarly, the comparison between the experiment ($V85_{exp}$) and the fuzzy model, allows the carrying out of the following considerations. If the threshold of 10% is held to be acceptable, then the only curve in which the fuzzy model works poorly is No. 12 (16.17%). Here the visibility available is compatible with that required by the standard, for which the reason for the failure is to be found in variables not yet considered within the model. This anomaly, indeed, would have to constitute the starting point for the introduction of further variables that increasingly refine the final results.

At this stage of research, this was not done in order to assess the method in its essential lines but, as already stated, the fuzzy structure can be further enriched both in the quantity of significant data as well as variables representative of the phenomenon.

The reliability of the final results can also be verified through statistical procedures more or less known. In this work such control that is based on the direct measurement of $V85$ and on its confirmation with an algorithm present in literature obtained by an analysis of regression on data recorded in Greece that has demonstrated the best connection to the road in question with regard to other models. The results, from a numerical point of view, are very encouraging but it is not the entity of the precision that the present research intends to achieve but, rather, its possible developments in the practical engineering field.

In fact, at the stage of adaptation of an existing road, the designer studies a series of solutions that, in his view, should improve the drivers' safety. Very often safety is linked to the decrease or, in any case, to the variation of speed. It would be very interesting to have an instrument that allows the definition with certain precision of the various scenarios. The current models present in literature are generally based on a few variables, such as the radius, the CCRs, the development of the geometric elements. Therefore, modifications to road signs, visibility and conditions of light cannot be appreciated that, instead, are interventions often preferred by the designer with regard to the modifications of alignment, precisely because they have lower economic impact.

So the procedure to be followed would be to construct a general fuzzy model (that is valid for any typology of road), including within the variables of input also those which are mainly sensitive to the modifications that the designer intends to carry out, so as to effectively assess the repercussions that will be related to speeds held by the users.

Naturally, since this model has full and general application, it must be tried on multiple different road contexts.

6. CONCLUSION

The paper deals with the analysis of the drivers' behaviour by means of V85 speed, in order to verify the presence of road inconsistency that could lead to dangerous consequences for the road safety.

[RW 2 – 2] This procedure can be applied to the design of the existing roads, although it can also be adapted to newly constructed roads. In fact, the designer, prior to the introduction of the inputs of those variables that will be affected by his intervention, will be able to assess with great reliability the impact that such modifications will have on the speeds held by drivers.

Among the main advantages achieved with the present procedure the following can be mentioned:

- The model can be easily integrated with new variables or more rules when additional information becomes available. The tool, once established, not only is perfectly compatible with the increase of the data set but, this feature, increasingly refines the final result.
- With the inclusion of economic constraint, the problem may be integrated with techniques of operational research, in order to maximize a specific objective function.
- This methodology can support the audits contained in the traditional road geometrical standards when the design solutions are not completely satisfactory.
- It is possible to simulate scenarios of particular danger, suggested by the analysis of accidents.

The authors did not deepen the numerical aspect of the phenomenon, since the research, at its current stage, manages a limited data set with the consequence that the results may not be perfectly reliable. However, the proposed prediction model is already able to communicate with the maintainer to select the most appropriate variables in order to analyze and improve the consistency of speed.

The most sensitive aspect of this paper concerns the general applicability of the research. This could be interpreted in two ways:

1) The use of the model already calibrated on a new road similar, however, to that previously tested. This procedure, in principle, should not provide any benefit compared to existing studies in literature and the correctness of the final result would depend only on the diversity of the new road rather than the one on which the model was calibrated. For this reason it makes no sense to propose evaluations of the numerical processing because these would be extremely variable, depending on the route examined.
2) The methodology remains unchanged, but the model is modified in the function of the analyzed road through a new measurement campaign. As has been mentioned in previous sections, the data set affects the shape of membership functions, the nature and number of rules. In this way the model will never be the same as the previous one if not in scheme but in the face of a greater burden for the survey of new data, the reliability of the final results will be very high.

The advantage compared to the previous studies is not just to have better reliability of the V85 value. But, above all, to be able to identify the variables on which this result depends and directing maintenance operations to correct the lack of consistency. As an example, V85 value acquired from the Greek model does not give us the ability to perform sensitivity analysis on the variables involved. So, a value too high or too low of V85 can only be corrected by adjusting the variables in that simple formula, without knowledge of the actual weight taken by each of them or about elements that may have affected the phenomenon.

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SOMMARIO

APPLICAZIONE DI TECNICHE FUZZY PER LA DETERMINAZIONE DELLA VELOCITÀ OPERATIVA BASATA SULLA GEOMETRIA STRADALE

La velocità operativa è, certamente, una delle variabili più importanti nella gestione della sicurezza stradale. La sua determinazione è stata trattata negli ultimi anni attraverso analisi di tipo sperimentale che hanno confermato il suo stretto collegamento con il contesto entro cui i rilievi sono stati svolti. Infatti, sebbene tutti gli algoritmi proposti abbiano una struttura analitica molto semplice e di natura generale, è stato provato che possiedono una buona affidabilità solo nell'ambiente in cui sono stati desunti.

Oltretutto, lo sviluppo tecnologico oggi raggiunto dai moderni strumenti di misura permette la definizione del contesto stradale in formato digitale ed in modo economicamente accettabile, anche se il prodotto di tali rilievi è una enorme quantità di dati.

Pertanto, lo scopo di questo lavoro è stato quello di proporre una metodologia che permetta non solo l'ordinamento e la classificazione di numerosi dati importanti ma che sia anche in grado di riconoscere la presenza di dipendenze tra *le variabili coinvolte, spesso di difficile caratterizzazione analitica. La tecnica di clustering utilizzata per ordinare il data set è stata preliminare alla predisposizione di un modello fuzzy che ha tenuto conto di variabili usualmente presenti all'interno del contesto stradale e che ha restituito quale variabile di output la velocità operativa.*

Tale modello è stato applicato ad una strada extraurbana sita a Messina (Italia) ed i risultati raggiunti, verificati sia con rilievi sperimentali che con gli algoritmi presenti in letteratura, sono molto incoraggianti ed invitano ad approfondire il presente studio.

PAROLE CHIAVE

Velocità operativa, Fuzzy logic, Sicurezza stradale, Incidentalità, Visibilità, Geometria stradale

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