SETTING VARIABLE SPEED LIMITS USING DOMINANCE-BASED ROUGH SET APPROACH

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ABSTRACT

Speed has been identified as a key risk factor in road traffic injuries, influencing both the risk of road traffic crashes and the severity of the injuries that result from them.

Most road safety experts agree that the single most important contributor to road fatalities around the world is poor speed selection, commonly interpreted as the use of inappropriate vehicle speeds, or ‘speeding’, defined as ”excessive speed (driving above the speed limit) or inappropriate speed (driving too fast for the conditions, but within the limits)” (OECD/ECMT, 2006) (GRSP, 2008).

Current approaches for settings speed limits consist of two main methods: maximum statutory speed limits and speed zoning. The firsts are determined by every government basing on road class, the seconds are determined by managing authorities that can change maximum speed limits for a roadway section where the statutory limit is not appropriate: this roadway section is called “speed zone” and speed limits are set based on engineering investigation.

Normally speed limits are static and suggest the limit established by law or by traffic engineering practices, but these are not able to assist travellers when condition are different from prevailing roadway and traffic conditions.

The use of variable speed limit (VLS) control based on real time road, traffic and weather conditions can improve safety and increase the acceptance of the limits by the drivers.

A method for setting variable speed limits is presented in this paper, using a Decision Support System (DDS) based on Dominance-based Rough Set Approach (DRSA).

The proposed methodology is able to individuate a safe and credible speed limit - both in prevailing condition and adverse condition - on the basis of a decision model set up by means of preference information in terms of exemplary decisions provided by an expert panel.

This developed Decision Support System can be used for setting speed limits in Variable Speed Control Systems (VSCS) - that display in real time the current speed limit by variable message signs - or in ISA Systems, where the current speed limit is directly linked to the vehicle control system.

Keywords: Speed, variable speed limits, Decision Support System, Dominance-based Rough Set Approach (DRSA)

INTRODUCTION

Driving speed is an important road safety factor because there is a strong relationship between speed and both crash rate and injury severity (TRB, 1998),(Wegman, et al., 2006), (Aarts, et al., 2006), (SWOV, 2008). Furthermore, driving speed also influences accessibility, the environment, and quality of life. Thus, speed control is important for a variety of reasons and is continuously required to find a good balance between not always harmonious interests.

An appropriate speed for a road section in fact is a speed level that considers safety as the main goal, in the context of mobility and prevailing conditions such as operative conditions (i.e. traffic volume, percentage of heavy vehicles, accident rate), road geometric characteristics and road maintenance conditions. Speed limits have also to be credible in the meaning that road users have to regard them as logical under given conditions.

Nowadays excessive speed is a widespread social phenomenon in many countries. A large number of road users drive above limits set by national or local authorities on all types of roads. The proportion of car drivers above the speed limit for different types of roads in each countries but typically 40 to 50%, and up to 80% of drivers are driving above the posted speed limits (OECD/ECMT, 2006). Often there is a discrepancy between driver’s perception of a safe speed and the appropriate speed for the road section they travel.

Given the strong relationships between speed and crash risk and crash severity, many casualties could be prevented if drivers better complied with the speed limits.

So, recommendation of appropriate speed limits on road section (safe and credible at the same time) has to be the focus of speed management for every country’s managing authority.

Normally the national speed limits consist of a limited number of general speed limits and a variety of local speed limits. General speed limits cannot correspond to the appropriate speed on all roads and at all times, so local speed for every “speed zone” is required.

Several methods and models have been developed to assess the most appropriate speed limit for a speed zone. Different countries have diverse ways of defining appropriate speed on they road networks: every government determines the national priorities that can also evolve over time as societies set different priorities for their road system.

Speed limits always are determined on the basis of the prevailing condition of the speed zone, so suggest to drivers the speed he can drive safely in average condition. But accident risk increase drastically in adverse condition, such as wet/slippery roads decreased visibility, darkness and sharp curves, etc… especially since drivers do not adapt speeds to lower friction or impaired visibility.

For this reason an increasing number of countries now implement variable and dynamic speed limits, whereby the limit is varied according the time of the day, the seasons, or takes into account the actual traffic condition on the road (OECD/ECMT, 2006).

Variable speed limits are activated through general criteria, such as the time of the day, the season, certain weather condition and are usually set by each country at national level. Dynamic speed limits on the contrary are generally activated at a given time, based on traffic volume or other criteria, and often make use of dynamic advisory speed sign. This type of speed limits, without distinction, are all known as Variable Speed Limits (VSL).

Variable speed limits systems – also known and Variable Speed Control Systems (VSCS) - can be considered a type of Intelligent Transportation System (ITS) that utilizes traffic speed and volume detection, weather information and road surface condition technology to determine appropriate speeds at witch drivers should be traveling, given current roadway and traffic condition (Robinson, 2000).

Variable speed limits system are used in order to satisfy one or more of the following purpose (Sisiopiku, 2001):

1. Provide early warning to motorists of slow traffic or hazardous roadway conditions;
2. Influence driver behavior and increase driver motivation to obey the posted speed limit;
3. Minimize crash risk and improve traffic safety;
4. Stabilize and smooth traffic flows.

To the current traffic systems - organized highly statically - ITS add dynamics (change in times) and flexibility (adaptation to circumstances); with the right information at the right place and at the right time, ITS offer the possibility to respond to specific condition (Wegman, et al., 2006).

The most promising ITS application, in addition to dynamic speed limits systems, are Intelligent Speed Assistance (ISA) systems: they are intelligent speed management systems which are based in information transfer between surroundings and vehicle; the vehicle receives information about the desired or legal speed limit from the surroundings and reacts to it, with simple warnings or intervening on accelerator pedal (Wegman, et al., 2006), (Carsten, et al., 2005).

EXPERIENCES WITH VARIABLE SPEED LIMITS

A number of VSC Systems have been successfully implemented during last years and they can be grouped into four application categories (Hellinga, et al., 2007):

- Speed control in response to adverse weather and road surface conditions;
- Heavy vehicle speed control;
- Work zone speed control;
- General-purpose congestion control.

Many experiences with variable speed limits have been done in various countries during last years. In Australia, Great Britain, Germany, Finland, France, and the Netherlands, variable speed limits are used since many years (in Germany firsts since 1970's) to control speed, promote safety, and reduce congestion.

Examples of variable speed limits system application in U.S.A. and Europe were described at the 2000 Annual Meeting of the Transportation Research Board (Robinson, 2000).

Experiment in speed management by variable speed limits have been done on the A2 Motorway in the Netherlands (Van de Hoogen, et al., 1994), on the M25 Controlled Motorway in the U.K. (UK Highway Agency, 2004) and on the A7 motorway in France (OECD/ECMT, 2006), (ASF, 2008), (Vitet, 2010). For five years between 2003 and 2007 the Swedish Road Administration (SRA) has launched a trial project on variable speed limits (OECD/ECMT, 2006), (Vägvertek, 2007); dynamic speed control on the entire main road network around the metropolitan area of Barcelona since 2007have been implemented (Serrano Sadurní, et al., 2010), (Servei Català de Trànsit, 2011); a program of field operational test (called “Dynamax”) for assessment of effects of dynamic speed limits for different applications is underway from 2009 on three Dutch motorways (Stoelhorst, et al., 2010).

In U.S.A. the National Cooperative Highway Research Program (NCHRP), managed by the Transportation Research Board, has a study (Project 03-59 *“Assessment of Variable Speed Limit Implementation Issues”*) underway to assess the impact of, and issues associated with implementation of variable speed limits and to develop operational test plans for the most promising applications (NCHRP, 2002), (TRB, 2010). US Department of Transportation’s Federal Highway Administration (FHWA) solicited and carried out applications for field tests of VSL systems in work zones in Maryland, Michigan and Virginia (Warren, 2003), (Lyles, et al., 2004); from 2007 new rural VSL system has been installed by the Wyoming Department of Transportation along Interstate 80 in the southeastern part of the state (Buddemeyer, et al., 2010).

For proper operation of Variable Speed Control Systems (VSCS), a synergy of real-time traffic and weather data collection, data processing and dynamic speed limit display is required (Sisiopiku, 2001).

For real-time data collection various methods are used such as loop detectors impeded in the pavement, overhead radar, visibility detector, weather stations, pavement sensors, etc.

Data processing and speed limit calculation are collected and processed by an operator at a traffic management centre or by a central server for automatic response. Typically rule-based response logic algorithms to determine safe speed limits based on real-time data are used: matrices of advisory speed and corresponding condition, simple reductions from the normal speed limit in five-mph increments basing on real-time collected data, logic tree, fuzzy logic control algorithms, and so on. All that logic algorithms are very simple and consider only few variables in speed limit selection, with the exception of fuzzy logic control algorithms. This problem solving technique, has been used and tested in variable speed limit system design and implementation in Arizona since 1998 (Arizona Department of Transportation, 1998), and to develop a model for speed control according to vehicle and road condition simultaneously (Pouramini, et al., 2011).

After data processing and speed limit calculation the new speed limit is displayed on variable message signs, in many cases used in conjunction with variable message displays that provide warnings of hazardous conditions or display speed reduction warning information.

Using the newest ITS technologies (Intelligent speed Adaptation - ISA), speed limits can also be linked with vehicle control systems that can intervene directly on vehicle speed.

PROBLEM DEFINITION

Considering speed limits importance in speed management policies, aim of the present paper is the definition of a decision-support tool that can provide speed zone limits, both in prevailing and adverse conditions, using a multi-criteria decision model.

DATA

In the presented work, data is composed by a set of 125 road sections on Italian rural roads, and precisely two lane roads with statutory speed limit of 90km/h. Road sections have been selected taking into account geometric, operative, maintenance characteristics and accident rate, obtaining speed zones with homogeneous characteristics and at least 300 m in length.

Speed zone characteristics are described by a set of attributes, which can well describe operative conditions, geometric characteristics, and maintenance conditions of every road section, and also some attributes that can describe the current condition of weather and traffic in the considered road section.

The twelve considered attributes are the following (the descriptors of the attributes have been reported within parentheses):

A_1= Lane width (in meters);
A_2= Shoulder width (in meters);
A_3= Shoulders conditions (high or low);
A_4= Road Signs (yes or no);
A_5= Pavement Condition (high, moderate and low);

A_6= Roadside Hazard Rating (1,2,3 or 4);
A_7= Accident Rate (high or low);
A_8= Adverse Alignment (yes or no);
A_9= Pavement surface (wet or dry);
A_{10}= Rainfall (no, moderate or heavy);
A_{11}= Wind (yes or no);
A_{12}= Fog (yes or no);
A_{13}=Traffic Volume (high or low).

It is important to remark that other and different attributes can be considered in speed zone definition, in relation to available data or/and Decision Maker (DM) choice.

Every attribute and its classification are described here in the following.

The attribute *"Lane width"* and *"Shoulder width"* respectively refer to the lane and the shoulder size (in meters): the larger are the lane and shoulder widths, the higher should be the recommended speed limit. The attribute *"Shoulder condition"* refers to the state of maintenance of shoulders: it is classified as high if shoulders are well identifiable, not overgrown and not soil covered, and as low if soil or vegetation do not allow to clearly recognize shoulders on road section. The attribute *"Road signs"* only indicates the presence or absence of pavement markings on the investigated road section. The attribute *"Pavement Condition"* describes the pavement condition as high, moderate and low. The *"Roadside Hazard Rating (RHR)"* is a measure of the roadside conditions including shoulder wide and type, side slope and presence/absence of fixed objects on the roadside (Zegeer, et al., 1988). Roadside hazard defined by Zegeer is ranked on a seven-point categorical scale from 1 (best) to 7 (worst). This scale has been adapted to Italian Roads and a four-point scale has been used, where level 1 allows higher speed limits and level 4 allows lower ones. The four categories of roadside hazard rating are defined as follows:

- RHR=1: presence of roadside barriers if required, correctly installed and by law; roadside free from obstacles (trees, poles, etc.) or embankments; recoverable in a run-off-road situation.
- RHR=2: presence of roadside barriers if required, but either not properly or not legally installed; possible presence of exposed trees, poles or other objects; marginally recoverable in a run-off-road situation.
- RHR=3: limited presence of roadside barriers in flyover, steep and high slope, etc.; exposed rigid obstacles (trees, poles, etc.) and embankments; virtually non-recoverable in a run-off-road situation.
- RHR=4: absence of roadside barriers, cliff or vertical rock cut, non-recoverable in a run-off-road situation.

The attribute *"Accident rate*" characterizes the safety conditions of each section. For each section the accident rate is defined as the ratio between the observed number of accidents (only fatal and injury crashes are taken into account) and the risk exposure (given by the product of all traffic flows in the observed period for the section length); the investigated period has to be at least two years long to be significant and no longer than five years in order to avoid non stationary phenomena. In this study a five years long period is used. The evaluation of safety level is based on a statistical procedure and it is classified as low hazardous section or high hazardous section. The*"Adverse Alignment"* attribute includes road features with vertical and/or horizontal alignment which differs significantly from the alignment of the general road. Adverse alignment segments typically reduce operating speeds below the general speed limit for the section. Examples of adverse alignment segments are: small radius curve, winding road, curve after long straight, narrow pavement widths and shoulders, road bumps, etc. The presence or the absence of an adverse alignment in the measured section has been marked. The attribute "*Pavement Surface*" characterizes the conditions of the road surface in terms of wet or dry. The attribute "*Rainfall*" characterizes the weather conditions and is classified in terms of no rainfall, moderate rainfall (up to 6 mm/h) and heavy rainfall (over 6 mm/h).The attributes "*Wind*" and "*Fog*" only indicates respectively the presence or absence of wind and fog in the road section; the attribute Wind is classified as present when wind-speed is up to 30 km/h, and the attribute Fog is classified as present when the visibility is less than 1000 m. Finally the attribute *"Traffic Volume"* refers to the traffic level on the investigated road section; it has been obtained from managing authorities' official data and it is classified as low, moderate and high considering as threshold6.000 ad 20.000 vehicles/day: i.e. Traffic Volume is low if lower than 6.000 vehicles/day, is medium if higher than 6.000 and lower than 20.000 vehicles/day, and is high if higher than 20.000 vehicles/day.

EXPERT PANEL SELECTION

The set of the 125 road sections selected on Italian rural roads, each one described by the set of the 13 chosen attributes described above, has been submitted to an Expert Panel.

The Expert Panel function is to assess a safe speed limit for every investigated speed zone, only on the basis of its characteristics (classified as described above) and some photos. Every Expert Panel component have to select the most appropriate speed limit (in terms of safety) among 50, 60, 70, 80 and 90 km/h - the last one is the statutory speed limit for the investigated type of roads.

Different members, with different priorities and purposes in speed limits selection, can compose the Expert Panel. For example, it can be composed by members of managing authority, road safety experts, road users, government delegates, and so on. The final decision – i.e. a safe speed limit for each selected speed zone – can be the mean of every Expert Panel member selected value or can be selected as the value in they agree on.

In the present case study the Expert Panel was composed by three safety experts and the final decision about the safe speed limit for every selected speed zone has been taken by common agreement.

METHODOLOGY

The basic idea of this paper is to develop an intelligible and user friendly tool that can suggest to users a safe speed limit and at the same time that can easily explain them the reasons of that suggesting, in order to avoid the "*black box*" effects of many alternative decision support methods. More precisely the aim of this work is to represent the experience of one or more experts in a set of *"if …, then …"* decision rules that synthesize some exemplary decisions about speed limits supplied by them.

Furthermore, in order to consider multiple attributes in the decision process for setting speed limits in speed zone, a multi-criteria decision model have to be used.

This multi-criteria decision model adopted in this study is based on the Dominance-based Rough Set Approach (DRSA) (Greco et al., 1999) (Greco et al., 2001)(Greco et al., 2002b) (Greco et al., 2005) (Slowinski et al., 2005). This approach is an evolution of Classical Rough Set approach (CRSA) developed by Pawlak (Pawlak, 1991) that allows applying it in multi-criteria problems.

DRSA has been chosen because it has two fundamental advantages over other approaches:

- DRSA requires the preference information in terms of exemplary decisions which are very natural and easy to be supplied by the decision maker (contrary to some model parameters required by other competitive multiple criteria methods, such as weights of criteria, trade-offs between criteria, thresholds, and so on) (Fishburn, 1967) (Mousseau, 1993);
- DRSA produces a decision model expressed in terms of easily understandable "*if…, then…*" decision rules which permits to control the decision process and to avoid the *"black box"* effects of many alternative decision support methods (Greco et al., 2005) (Slowinski et al., 2009).

The application of Dominance-based Rough Set Approach (DRSA) for multi-criteria decision model development is presented in the following section.

DOMINANCE ROUGH SET APPROACH TO DEVELOP A MULTI-CRITERIA DECISION MODEL FOR SETTING SPEED LIMITS

The multiple criteria decision support system proposed in this paper aims to suggest to managing authority the most appropriate speed limit for every speed zone individuated, known geometric and operative characteristics, maintenance conditions and also some attributes describing current weather and traffic condition, basing only on exemplary decisions. In the following subsections is presented the application of DRSA in multi-criteria decision model for setting speed limits.

INFORMATION TABLE AND DOMINANCE RELATION

The base of a Rough Set analysis is an *information table*. The rows of the table are labelled by *objects*, whereas columns are labelled by *attributes* and entries of the table are *attribute-values*, called *descriptors*. In the present case every row of the table is a road section, and every column contains technical and functional parameters conveniently selected to describe road sections.

The set *Q* is, in general, divided into set *C* of *condition attributes* and set *D* of *decision attributes*. The notion of attribute differs from that of *criterion*, because scale of a criterion (its value set) has to be ordered according to decreasing or increasing preference, while the scale of a regular attribute does not have to be ordered.

In the present case U is a set of 125 road sections on Italian rural roads, (two lane roads with statutory speed limit of 90km/h) and Q is composed by the attributes that describe them (i.e. condition attributes, *C*) and the speed limit recommended by an expert panel as the most appropriate (in terms of safety) among 50, 60, 70, 80 and 90 km/h (i.e. decision attribute, *D*). The information table (i.e. the data set) and the expert recommended speed limit for each road section constitute the exemplary decision; they have been shown in Table 1.

Table 1 Abstract of the data set with Expert Panel Decision: "*table of exemplary decision*"

	Attributes													
	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9	A_{10}	A_{11}	A_{12}	A_{13}	D
Road Section	Lane Width	Shoulder Width	Shoulder Condition	Road Signs	Pavement Condition	RHR	Accident Rate	Adverse Alignment	Pavement surface	Rainfall	Wind	Fog	Traffic Volume	Expert Panel Decision
1	3.25	0.00	L	Y	M	1	L	N	DRY	N	N	Y	L	80
2	3.25	1.00	H	Y	H	1	H	N	WET	L	N	N	L	80
3	3.50	1.00	L	Y	M	2	L	Y	DRY	N	N	Y	L	70
4	3.50	1.00	H	Y	M	4	H	Y	WET	L	Y	N	H	60
5	3.50	0.00	L	N	H	2	L	N	WET	L	N	N	L	80
6	3.50	1.00	H	Y	L	1	L	Y	DRY	N	N	N	L	80
7	3.50	1.25	H	Y	H	2	H	Y	WET	H	N	Y	H	60
8	3.50	0.00	L	N	L	4	H	Y	DRY	N	N	Y	H	50
9	3.75	0.00	L	N	M	2	L	Y	DRY	N	N	Y	H	70
10	3.75	0.75	L	Y	L	3	H	Y	DRY	N	N	Y	H	50
….	…	…	…	…	…	…	…	…	…	…	…	…	…	…
….	…	…	…	…	…	…	…	…	…	…	…	…	…	…
….	…	…	…	…	…	…	…	…	…	…	…	…	…	…
120	3.50	1.00	H	Y	H	2	L	Y	DRY	N	N	N	L	90
121	3.75	1.25	H	Y	H	3	L	N	DRY	L	N	N	L	90
122	3.75	0.00	L	N	M	2	L	N	DRY	N	N	N	L	90
123	3.50	1.25	H	Y	M	3	L	N	DRY	N	N	N	L	90
124	3.75	0.00	L	N	M	1	H	N	DRY	N	N	N	L	90
125	3.50	1.25	H	Y	H	2	H	N	DRY	L	N	N	L	90

Assuming that all condition attributes $q \in C$ are criteria, let $\succeq_q$ be a *weak preference* relation on U with respect to criterion q such that $x \succeq_q y$ means "*x is at least as good as y with respect to criterion q*". It is supposed that $\succeq_q$ is a total pre-order, i.e. a strongly complete and transitive binary relation, defined on U on the basis of evaluations $f(\cdot,q)$.

Furthermore, assuming that the set of decision attributes D (possibly a singleton {d}) makes a partition of U into a finite number of classes, let $Cl=\{Cl_t, t \in T\}$, $T=\{1,...,n\}$, be a set of these classes such that each $x \in U$ belongs to one and only one $Cl_t \in Cl$. Assuming that the classes are ordered, i.e., for all $r, s \in T$, such that $r>s$, the objects from Cl_r are preferred to the objects from Cl_s.

The above assumptions are typical for consideration of a *multiple-criteria sorting problem* (also called *ordinal classification problem*) (Greco, et al., 2002a). In the present case the set of decision D attributes is a singleton given by the attribute "recommended speed limit" which partitions the set U of the 125 road sections in the classes:

- Cl_1composed of road sections with recommended speed limit of 50 km/h;
- Cl_2composed of road sections with recommended speed limit of 60 km/h;
- Cl_3composed of road sections with recommended speed limit of 70 km/h;
- Cl_4composed of road sections with recommended speed limit of 80 km/h.

- Cl_5composed of road sections with recommended speed limit of 90 km/h.

DOMINANCE BASED APPROXIMATION

These classes are ordered according to the preference of recommended speed limit, such that $x \succ y$ whenever $x \in Cl_r$, $y \in Cl_s$ and $r \geq s$.

Partition of the set U in classes, respecting dominance relationship, allows approximating sets in unions of classes, called *upward union* and *downward union* of classes, respectively:

$$Cl_t^{\geq} = \bigcup_{s \geq t} Cl_s$$

$$Cl_t^{\leq} = \bigcup_{s \leq t} Cl_s$$

With $t = \{1, 2, \dots, n\}$.

Thus, the statement $Cl_1^{\geq} = \bigcup_{s \geq t} Cl_s$ means "*x* belongs to at least class Cl_t", while $x \in Cl_t^{\leq}$ means"*x* belongs to at most class Cl_t".

In the case study the *upward union classes* are:

- $Cl_1^{\geq}$composed of road section with recommended speed limit "at least" 50 km/h (≥50 km/h)
- $Cl_2^{\geq}$composed of road section with recommended speed limit "at least" 60 km/h (≥60 km/h);
- $Cl_3^{\geq}$composed of road section with recommended speed limit "at least" 70 km/h (≥ 70 km/h);
- $Cl_4^{\geq}$composed of road section with recommended speed limit "at least" 80 km/h (≥ 80 km/h);
- $Cl_5^{\geq}$composed of road section with recommended speed limit "at least" 90 km/h (≥ 90 km/h);

The *downward union classes* are:

- $Cl_1^{\leq}$composed of road section with recommended speed limit "at most" 50 km/h (≤50 km/h);
- $Cl_2^{\leq}$composed of road section with recommended speed limit "at most" 60 km/h (≤60 km/h);
- $Cl_3^{\leq}$ composed of road section with recommended speed limit "at most" 70 km/h (≤70 km/h);
- $Cl_4^{\leq}$ composed of road section with recommended speed limit "at most" 80 km/h (≤80 km/h).
- $Cl_5^{\leq}$ composed of road section with recommended speed limit "at most" 90 km/h (≤90 km/h).

Let us remark that $Cl_1^{\geq}=Cl_n^{\leq}=U$, $Cl_n^{\geq}=Cl_n$ and$Cl_1^{\leq}=Cl_1$.

In the present application the upward union classes $Cl_1^{\geq}$and the downward union classes $Cl_5^{\geq}$contain all the 125 road section considered: in fact for all considered road section speed limit is always at least 50 km/h and at most 90 km/h. Furthermore, for $t=2,...,n$, we have: $Cl_{t-1}^{\leq}=U- Cl_t^{\leq}$ and $Cl_t^{\geq}= U - Clt-_1^{\leq}$.

The key idea of rough sets is approximation of knowledge expressed in terms of decision attributes by knowledge expressed in terms of condition attributes. This means to explain the partition of the decision attribute, according to the recommended speed limits, in terms of technical and functional parameters expressed by the conditional attributes. In DRSA, the knowledge approximated is a collection of *upward and downward unions of classes* and the "*granules of knowledge*" are sets of objects defined using *dominance relation* instead of *indiscernibility relation*.

That is *x dominates y* with respect to $P \subseteq C$ if $x \in U$, the "*granules of knowledge*" used for approximation in DRSA are:

- a set of objects dominating x, called *P-dominating set*, $D_P^+(x) = \{y \in U: y\ D_P\ x\}$
- a set of objects dominated by x, called *P-dominated set*, $D_P^-(x) = \{y \in U: x\ D_P\ y\}$

Moreover, above dominating sets and dominated sets are "*granules of knowledge*" in the sense that it is supposed that road sections dominating x should be classified with at least the same recommended speed limit than x as well as road sections dominated by x should be classified with at most the same recommended speed limit. For instance, if the considered criteria are "*pavement condition*" and "*traffic volume*", both of them evaluated on three levels scale with high, moderate and low, and road section x is evaluated as moderate with respect to pavement condition as well as with respect to traffic volume, then:

- $D_P^+(x)$ is composed of all road sections moderate or low with respect to pavement condition and traffic volume,

and

- $D_P^-(x)$ is composed of all road sections moderate or high with respect to pavement condition and traffic volume.

DECISION RULES AND PROCEDURES FOR GENERATION OF DECISION RULES

The dominance-based rough approximations of *upward and downward unions of classes* can serve to induce a generalized description of objects contained in the information table in terms of "*if..., then...*" decision rules (Greco, et al., 2002a) (Greco, et al., 2005) (Slowinski, et al., 2005).

Since the aim is to underline the functional dependencies between condition and decision attributes, a decision table may also be seen as a set of *decision rules*. These are logical statements of the type "*if …, then …* ", where the premise (condition part) specifies values assumed by one or more condition attributes (description of *C*-elementary sets) and the conclusion (decision part) specifies an assignment to one or more decision classes. Therefore, for a given *upward or downward union of classes*, $Cl_t^{\geq}$ or $Cl_s^{\leq}$, the decision rules induced under a hypothesis that objects belonging to $\underline{P}(Cl_t^{\geq})$ or $\underline{P}(Cl_s^{\geq})$ are *positive* and all the others *negative*, suggest a *certain* assignment to "at least class Cl_t" or to "at most class Cl_s", respectively; on the other hand, the decision rules induced under a hypothesis that objects belonging to the intersection $\overline{P}(Cl_t^{\geq}) \cap \overline{P}(Cl_t^{\geq})$ are *positive* and all the others *negative*, are suggesting an *approximate* assignment to some classes between Cl_s and Cl_t ($s<t$).

Assuming that, for each $q\in C$, $V_q \subseteq \mathbb{R}$ (i.e. V_q is quantitative) and that, for each $x,y\in U$, $f(x,q)\geq f(y,q)$ implies $x \succeq_q y$ (i.e. V_q is preference-ordered), the following types of decision rules can be considered:

1) <u>$D_{\geq}$-*decision rules*</u>with the following syntax:

   If $f(x,q_1)\geq r_{q1}$ *and* $f(x,q_2)\geq r_{q2}$ *and …* $f(x,q_p)\geq r_{qp}$, *then* $x\in Cl_t^{\geq}$,

   Where $P=\{q_1,...,q_p\}\subseteq C$, $(r_{q1},...,r_{qp})\in V_{q1}\times V_{q2}\times ...\times V_{qp}$ and $t\in\{2,\dots,n\}$;

2) <u>$D_{\leq}$-*decision rules*</u> with the following syntax:

   If $f(x,q_1)\leq r_{q1}$ *and* $f(x,q_2)\leq r_{q2}$ *and ...* $f(x,q_p)\leq r_{qp}$, *then* $x\in Cl_t^{\leq}$,

   where $P=\{q_1,...,q_p\}\subseteq C$, $(r_{q1},...,r_{qp})\in V_{q1}\times V_{q2}\times ...\times V_{qp}$ and $t\in\{1,\dots,n-1\}$;

An object $x\in U$ *supports* decision rule *r* if its description is matching both the condition part and the decision part of the rule. The decision rule *r covers* object *x* if it matches the condition part of the rule.

Procedures for generation of decision rules from a decision table use an inductive learning principle. The objects are considered as examples of classification. In order to induce a decision rule with a univocal and certain conclusion about assignment of an object to decision class *X*, the examples belonging to the *C*-lower approximation of *X* are called *positive* and all the others *negative*. Analogously, in case of a possible rule, the examples belonging to the *C*-upper approximation of *X* are positive and all the others negative.

With respect to Table 1 the DRSA gives back 1670 decision rules in the *"if….then…"* form, and more precisely:

- 245 decisions recommend a speed limit ≥ 90 km/h;
- 463 decisions recommend a speed limit ≥ 80 km/h;
- 253 decisions recommend a speed limit ≥ 70 km/h;
- 97 decisions recommend a speed limit ≥ 60 km/h;
- 207 decisions recommend a speed limit ≤ 50 km/h;
- 184 decisions recommend a speed limit ≤ 60 km/h;
- 140 decisions recommend a speed limit ≤ 70 km/h;
- 81 decisions recommend a speed limit ≤ 80 km/h.

Every decision rule specifies the recommended speed limit and the reasons why it has been recommended; for every rule it is also possible to know which objects (example cases on information table) support the rule. The possibility of recognizing the examples supporting specific decision rules allows the expert panel members to understand and discuss the set of decision rules, which can be also easily revised if required.

In table 2 some examples of the 1670 decision rules have been reported, indicating also the road sections from Table 1 that support the considered rule.

It is worth noting that an algorithm specifically developed by the authors has implemented the induction of decision rules, which is based on the DRSA methodology. For the induction of decision rules it is also available a free software, called "4eMka2", free of charge at the web address: http://idss.cs.put.poznan.pl/site/139.html.

After discussion, the expert panel accepted the set of the 1670 decision rules to be the decision model for setting speed limits on speed zone.

Table 2: Examples of discovered decision rules

If…	then…	Objects (road sections) of the exemplary decision that support the rules
Lane Width ≥ "3.75 m" and *Shoulder Width* ≥ "1. 25 m" and *Pavement Condition* is "high" *and Pavement Surface* is dry	$Speed\ Limit \geq 90\ km/h$	108, 121
Shoulder condition are high and *Roadside Hazard Rating* ≤"3" and *Rainfall* is ≤ "moderate" and *Traffic Volume* is ≤ "medium"	$Speed\ Limit \geq 80\ km/h$	2, 6, 19, 51, 68, 80, 97, 100, 101, 104, 105, 107, 108, 109, 112, 113, 116, 120, 121, 123, 125
Lane Width ≥ "3.50 m" and *Road Signs are present and* Adverse Alignment are not present and *Pavement Surface* is dry	$Speed\ Limit \geq 70\ km/h$	17, 18, 25, 30, 34, 40, 52, 80, 87, 102, 105, 107, 108, 111, 112, 113, 115, 116, 117, 118, 119, 121, 123, 125
Shoulder Width ≥ "0. 50 m" and *Road Signs are present and Rainfall* is ≤ "moderate" and *Traffic Volume* is ≤ "low"	$Speed\ Limit \geq 60\ km/h$	2, 3, 6, 19, 25, 32, 38, 51,68, 72, 77, 80, 82, 93, 97, 98, 101, 104, 105, 107, 108, 109, 112, 113, 116, 120, 121, 123, 125
Shoulder Width ≤ "0.00 m" and *Roadside Hazard Rating* ≥ "4" and Accident Rate is high	$Speed\ Limit \leq 50\ km/h$	8, 14, 22, 24, 45, 75
Lane Width ≤ "3.25 m" and *Shoulder Width* ≤ "0.70 m" and *Shoulder condition* are "low" and *Pavement Condition* is ≥"low"	$Speed\ Limit \leq 60\ km/h$	15, 22, 37, 38, 57, 88
Lane Width ≤ "3.50 m" and *Shoulder Width* ≤ "1.00 m" and *Pavement Condition* is ≥"medium" and Adverse Alignment are present and Windis present	$Speed\ Limit \leq 70\ km/h$	4, 15, 42, 61, 62, 73, 89, 98
Lane Width ≤ "3.70 m" and *Shoulder Width* ≤ "1.20 m" and Adverse Alignment are present and *Traffic Volume* ≥ "medium"	$Speed\ Limit \leq 80\ km/h$	4, 8, 16, 28, 33, 35, 39, 45, 55, 59, 62, 64, 70, 73, 74

APPLICATION OF THE DECISION MODEL

Using the DRSA, some decision rules in the following form: *"if road section characteristics are… and environmental conditions are …, then the recommended speed limit have to be at least/can be at most …"* have been generated. These decision rules express the experience of one or more experts and synthesize the exemplary decisions about speed limits supplied by the experts reported in table 1.

Spending the knowledge contained in the exemplary decision, is possible to "extend" it to new cases (i.e. new road sections): taking into account a new road section only described by some attributes, every time that the "*if-part*" conditions are satisfied also the consequence (the "*then-part*") is satisfied.

The developed Decision Support System (DSS) actually uses specifically developed algorithm, which can easily interact with DRSA output, i.e. the decision rules.

Giving as input the new road section characteristics, the algorithm uses decision rules generated by DRSA and gives back a recommended speed limit. The algorithm also provides the most important decision rules that can help decision makers to understand the reasons of the suggested speed limit.

For example, for a road section characterized by the follow attributes values:

- Lane width (A_1) =3.50 m
- Shoulder width (A_2) =0.50 m
- Shoulders conditions (A_3) = Low
- Road Signs (A_4) = Present
- Pavement Condition (A_5) = High
- Roadside Hazard Rating (A_6) =2
- Accident Rate (A_7) = High

- Adverse Alignment (A_8) = Not present
- Pavement surface (A_9) = Wet
- Rainfall (A_{10}) = Moderate
- Wind (A_{11}) = Not present
- Fog (A_{12}) = Not present
- Traffic Volume (A_{13}) = Low

the DSS returns 72 decision rules:

- 24 of them recommend a speed limit ≥ 60 km/h;
- 34 of them recommend a speed limit ≥ 70 km/h;
- 2 of them recommend a speed limit ≤ 60 km/h;
- 4 of them recommend a speed limit ≤ 70 km/h;
- 8 of them recommend a speed limit ≤ 80 km/h.

and the algorithm calculates the recommended speed limit for the road section. It is computed as the value that satisfies all decision rules returned by the DRSA.

For the example case, does not exist a speed limit satisfying all the suggestions, because there is not a speed limit value that is not smaller than 60 km/h, not smaller than 70 km/h and at the same time not higher than 60 km/h, not higher than 70 km/h and not higher than 80 km/h. So, the rules supported by larger and larger numbers of road section in the original data base need to be considered, until the set of remaining rules becomes consistent with a unique value of the speed limit. In this case a support of at least 12 road sections (objects) is required to satisfy all the rules. Taking into account decision rules supported by at least 12 road sections, the algorithm returns:

- 24 of them recommend a speed limit ≥ 60 km/h;
- 34 of them recommend a speed limit ≥ 70 km/h;
- 2 of them recommend a speed limit ≤ 70 km/h;
- 8 of them recommend a speed limit ≤ 80 km/h;

so the speed limit satisfying all the suggestions is 70 km/h (because 70 km/h is not smaller than 60 km/h and not smaller than 70 km/h, and at the same time not larger than 70 km/h and not larger than 80 km/h).

The algorithm furthermore shows the most important decision rules, with the aim to explain to the decision-maker (DM) the reasons why the expert panel suggests a specific speed limit for the investigated road section. Obviously it is not reasonable to submit too many decision rules to the DM, and only the most supported rules recommending the exact value of the speed limit (and precisely the lower and the upper limit) are presented to the DM. For the example case they are:

- *"If the Roadside Hazard Rating is ≤ 2 and Adverse Alignment is not present then Speed Limit can be ≥ 70 km/h"*
- *"If the Shoulder Width is ≤ 1.00 m and Roadside Hazard Rating is ≥ 2 and Accident Rate is high and Pavement Surface is wet then Speed Limit have to be ≤ 70 km/h"*

Using them, the DM can understand which are the road section characteristics or weather and traffic conditions that have led up to this speed limit: it can be higher than 70 km /h because the RHR is smaller or equal than "2" and there are not adverse alignment for the selected speed zone, but at the same time it have to be smaller than 70 km/h because the pavement surface is wet, the accident rate for this speed zone is high, the RHR is higher than "2" and shoulder width is smaller than 1.00 m.

It is import to remark that for each decision rules also possible to know which are the exemplary decisions on it is based, i.e. which are the exemplary decisions that the given rule is describing. This information is important because these are important elements permitting that the expert panel could critically evaluate the decision rules. If some member of the expert panel is not convinced by some decision rule, possibly there is some example to which should correspond a different decision in terms of recommended speed limits, such that, after revising the not convincing exemplary decisions, a new set of decision rules can be induced and again submitted to the approval of the Expert Panel until it is satisfied by the set of decision rules. This is concordant with posterior rationality of March (March, 1978), which advocates discovery of intentions of a decision maker instead of the interpretation of a priori position. In simple words for the experts is easier to give some examples of good decisions rather than explain the reasons for which a decision is good. In this sense the methodology we adopt, which is the Dominance-based Rough Set Approach (DRSA) that we are going to introduce in the next section, asks to the experts what for them is easier, i.e. a set of exemplary decisions, and gives them what for them is more difficult, i.e. a set of explanations about the goodness of the decisions. Moreover this explanation is expressed in a clear way that permits the experts to see what are the exact relations between the provided information and the final recommendation. In fact, many statistical methods express their results through a technical formulation that the users cannot understand without a specific background and consequently, very often those results are perceived as a *black box* whose recommendations have to be accepted because the "scientific authority" of the model guarantees that the result is "right". In this context, the aspiration of the DM to find good reasons to make decision is frustrated and raises the need for a more transparent methodology in which the relation between the original information and the final recommendation is clearly shown. Such a transparent methodology searched for has been called *glass box* (Slowinski, et al., 2009) and DRSA has proved to be its typical representative.

Furthermore, on the basis of the managing authority's current policies, engineering criteria, practices, and experience, the generated decision rules (that are the basis of the DSS) periodically can be evaluated and updated if necessary. In fact, the DRSA permits a simple and transparent system revision: it only requires updating the set of exemplary decisions from which the "*if…, then…*" decision rules are induced. The rules explain the decision policy adopted in the examples and, after acceptance, can be used to support new decisions.

Let us remark that the DSS developed herein can be used also in case not every road section characteristic is available (for example crash data).

CONCLUSION

A multi-criteria decision support instrument to suggest the most appropriate speed limits for speed zones, both in prevailing and adverse conditions, has been presented in this paper.

The model developed herein provides a safe speed limit using geometric, operative and maintenance road conditions and current condition of weather and traffic; it provides too some easily understandable decision rules that can help to explain the reasons for the suggested speed limit for the investigated road section.

The developed Decision Support System is based on Dominance-based Rough Set Approach (DRSA) which requires basic input information in terms of evaluation examples, i.e. exemplary decision about speed limits, and express the results of the decision analysis in a very understandable way using *"if…, then…"* rules.

The adopted Dominance-based Rough Set Approach presents several advantages over other approaches in terms of transparency and manageability and has permitted to develop an intelligible and user friendly multi-criteria decision model for setting speed limits in speed zone. DRSA produces a decision model expressed in terms of easily understandable "*if…, then…*" decision rules which permits to control the decision process and to avoid the "black box" effects of many alternative decision support methods, ensuring a high degree of transparency. The DRSA also permits a simple revision of the decision model because it only requires to update the set of exemplary decisions from which the "*if…, then…*" decision rules are induced. Moreover the model can be easily changed using different "condition attributes" - that means that the information that the decision makers used to suggest the speed limit can be totally changed - or using a "decision attribute" suggested by different experts with different purposes and priorities. In this way the system can be adapted to every approach, such us harm minimization, economic optimization, driver's choice, etc…

In this paper it is also presented a sample application of the built Decision Support System that uses a specifically developed algorithm that can easily interface with the DRSA output. Putting as input the investigated road section characteristics, the algorithm gives back a recommended speed limit. This speed limit can be used in Variable Speed Control Systems (VSCS), displaying in real time the current speed limit by variable message signs, or in ISA Systems

Because of its versatility the developed DSS can be adapted to every approach only changing the attributes that form the information table.

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