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FREEWAY SAFETY MANAGEMENT: CASE STUDIES IN ITALY

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Abstract. Road safety has since become one of the major factors for a description of the state traffic system and crashes are often due to bad made decisions by drivers in environments created by engineers. This study proposes an update of the previous version (Dell'Acqua *et al.* 2011a) to estimate V_{85}, for non-conditioned traffic flows on freeways. The databases used in the study come from a series of speed measurements and vehicle ranges on a stretch of freeway using a fixed measuring system. The produced model proved to be very reliable, with the greatest error in the estimation of V_{85}, being less than 6%. The model obtained was then applied to a stretch of freeway of approximately 20 km. Some significant correlations between DV_{85} (variation of V_{85} among successive stretches) and DN (the variation in the number of crashes among successive stretches) were found, which may be very useful in the management of safety on roads. In particular the obtained results have highlighted some aspects of motorway traffic. In addition, using the procedure illustrated, it has been possible to identify some particular 'black spots' due to the poor design co-ordination of the alignment, positioned between consecutive stretches (for approximately 2 km), with a difference in terms of $V_{85average}$ greater than 10 km/h.

Keywords: road safety, highway design, driver speed behavior, operating speed, crashes.

1. Introduction

Road safety has since become a worldwide priority and one of the major factors for a description of the state traffic system in terms of both positive and negative changes. Driver behavior is always a compromise between conditioning arising from a series of external factors (road conditions, environmental conditions, etc.) and a series of personal factors (caution, driving ability, psycho-physical state, etc. Many researchers have been dealing with the evaluation of the traffic accidents costs, other researchers have addressed driver speed behavior to identify all possible factors that may affect driving conditions during travel (Dell'Acqua, Russo 2011a, 2011b). In fact, crashes are often due to bad decisions made by drivers in environments created by engineers (Dell'Acqua, 2011). International research has thus suggested a variety of approaches to analyze the road traffic safety level on the basis of an assessment of accident rates and frequency (Discetti *et al.* 2011).

Nie *et al.* (2007) modeled operating speeds on horizontal curves using data collected from a road experiment involving volunteer drivers and a test vehicle in Ontario, Canada. Continuous speed data were collected using instrumentation within the test vehicle. Geometric features were determined using GIS software. Driver speed trends were modeled using ordinary the least squares regression. Operating speeds along a horizontal curve were modeled, as well as speed differential values when approaching and departing the curve. Himes and Donnell (2010) investigated the effects of roadway geometric design features and traffic flow on operating speed characteristics along rural and urban four-lane highways in Pennsylvania and North Carolina. A simultaneous equations framework was used to model the speed distribution, developing equations for the mean speed and standard deviation of speed for both travel lanes using the three-stage least squares estimator. This simultaneous equation modeling framework was first introduced by Shankar and Mannering (1998) to model speeds on a freeway segment in Washington State. It was later explored in depth and compared to limited information (e.g., OLS regression) and full-information (e.g., seemingly unrelated regression) modeling methods by Porter (2007).

Dixon *et al.* (1999) have conducted a basic research on speed prediction for rural multi-lane highways and urban and suburban arterials. For the purposes of this research, the project should focus on passenger car op-

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erating speeds, trucks, and recreational vehicles, and be developed in a manner that complements the existing two-lane rural highway design consistency module currently available in the IHSDM (Interactive Highway Safety Design Model). The association between vehicle operating speeds and geometric design features on these facilities could assist in several design functions, particularly when used in concert with the latest enhancements to the IHSDM crash prediction module. Examples of this include: assessing the need for climbing lanes, justification of maximum grades, evaluating proposed capacity-expansion projects, and assessing speed-safety relationships on horizontal curves. The findings from this research could also be used as a framework to perform level of service analysis on uninterrupted flow facilities. In the Highway Capacity Manual, estimating free-flow speeds is an important step in freeway and multi-lane highway operational performance evaluations.

Deardoff *et al.* (2011) in a study conducted in Dakota proposed an important report on the free flow speed in highway. Two team members using a radar gun and manual tally sheets collected 1668 speed observations at ten sites during several weeks. Each site had a unique posted speed limit sign ranging from 20 mi/h (30 km/h) to 75 mi/h (120 km/h). Five sites were on urban streets. Three sites were on multilane highways, and two on freeways. Goodness-of-fit test results revealed that a Gaussian distribution generally fit the speed distributions at each site at a 5% level of significance. The best-fit model had a correlation coefficient of +0.99. The posted speed limit variable was significant at 5% level of significance. Examining data by highway type revealed that average free-flow speeds are strongly associated with posted speed limits with correlation coefficients of +0.99, +1.00 and +1.00 for urban streets, multilane highways, and freeways, respectively. Dell'Acqua *et al.* (2011a) proposed a model for estimating operative speed on motorways. The research is survey based, and takes into account various geometric conditions, making it possible to find the variables that influence operative speed in the Free Flow conditions. The research is survey-based, and takes into account various geometric conditions, making it possible to find the variables that influence V_{85}. In particular, the study proposed in the next paragraphs is an update of the previous version (Dell'Acqua *et al.* 2011a) to estimate V_{85}, for non-conditioned traffic flows on freeway.

2. Data Set

The data used in the study were collected on a stretch of the A3 situated in the south of Italy. The stretch is located between the distance marker at 195.000 km (Castrovillari interchange) and another at 290.000 km (Grimaldi interchange). The geometric variables measured in each section are shown in Table 1.

3. Recording Vehicle Speed and Traffic Flow

A survey station was placed at each section, (as indicated in Table 1) to record the flow and speeds of the vehicles passing within a time interval *T*. The structure of the survey station is represented in Fig. 1. It consists of a

Table 1. Data set organization

Survey Nr. (sections)	Date	T Duration Survey [hour]	Distance [km]	Dir.	Slope [%]	Width section [m]	Curvature [1/m]	Tortuousness* [grad/km]	State of paving	Transverse slope [%]	Distance from motorway-exit [km]
1	21/02/10	3	246.000	N	−2.0	10.7	0.0000	5.3	dry	2.5	2.5
2	14/03/10	4	236.000	S	1.0	10.7	0.0000	5.3	dry	2.5	2.0
3	30/04/10	5	236.600	S	1.5	10.7	0.0000	5.3	dry	2.5	2.6
4	05/05/10	2	207.000	N	−0.5	8.7	0.0000	23.7	dry	2.5	1.5
5	11/05/10	4	205.000	N	4.5	8.7	0.0000	24.7	dry	2.5	2.1
6	18/05/10	3	204.800	N	4.5	8.7	0.0000	26.0	dry	2.6	2.1
7	18/05/10	2	205.200	N	−4.0	8.7	0.0000	26.0	dry	2.4	1.9
8	27/05/10	4	243.200	N	−1.0	10.7	0.0012	12.0	dry	5.0	2.0
9	14/09/10	2	195.700	N	3.5	8.7	0.0014	28.0	dry	5.5	1.2
10	30/09/10	3	209.500	N	0.1	8.7	0.0010	22.0	dry	6.0	1.4
11	05/02/11	4	204.500	S	−4.5	8.7	0.0029	22.0	dry	7.0	2.6
12	11/03/11	2	204.600	N	4.5	8.7	0.0029	29.0	dry	7.0	2.7
13	18/04/11	2	289.400	N	−2.0	8.7	0.0011	22.0	dry	4.5	4.0
14	18/06/11	3	289.400	S	2.0	8.7	0.0011	29.0	dry	4.5	4.0
15	27/06/11	4	277.000	N	4.2	8.7	0.0027	21.00	dry	5.0	2.5

Note: * The meaning of this variable is explained in paragraph '*models for estimating*V_{85}'

digital television camera connected to a portable PC that shows the images it captures. The system is set up across a section of the road, as in Fig. 1, at a distance greater than 25 meters, allowing the vehicles that pass through the chosen section to be filmed. Knowing the distance between the three vertices, A, B and C shown in Fig. 1, it is possible to calculate 'fundamental 1' that joins points 1 and 2 and 'fundamental 2' that joins points 1' and 2'. With this information, assuming that there is uniform motion along the two 'fundamentals' (indicated as X_i) it is possible to obtain the speed of the vehicles along 'fundamental 1' and 'fundamental 2'. In fact, the PC is fitted with a card for the acquisition and elaboration of images that make it possible to read the images one frame at a time (1 *frame* = 1/25 sec). It is possible to count the number of frames it takes the vehicle to cover one of the two 'fundamentals'. The vehicle's speed is calculated from the relationship between the number of frames and the 'fundamentals'. To confirm the validity of the system and its calibration, checks were done at each reading, applying one of the two 'fundamentals' to three vehicles whose speeds were known. From the comparison between the speeds measured using the tachometer and those obtained by the system, it was possible to establish its reliability, which always resulted acceptable. The data acquired from the survey station were organized in the sequence shown in Table 2. Only the speeds of cars in free flow conditions ($V_p < 200$ pcphpl) were counted.

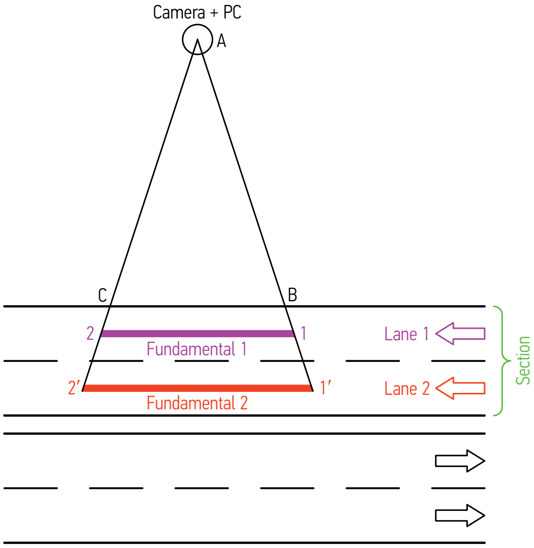

Fig. 1. Survey station

4. Identifying the Distribution for the Average Speeds

In general, the distribution of the vehicles' speeds (cars in particular) is best represented by normal distribution. The χ^2 test was carried out to verify the goodness of the above distribution law, the test has provided $P < 0.05$ for all surveys.

Table 3 shows the values of $V_{85observed}$ and $V_{85normal}$. $V_{85normal}$ was calculated using expression (1) for the law of normal distribution:

$$V_{85normal} = V_{average} + 1.04 \cdot st.dev. \quad (1)$$

The $V_{average}$ and the *st.dev.* used in (1) are shown in Table 3. The last column also shows $V_{85observed}$, i.e., the speed that was exceeded in only 15% of the readings. The $V_{85observed}$ and the $V_{85calculated}$ using (1) are very close, which further confirms the suitability of normal distribution for the observed speeds.

5. Models for Estimating V_{85}

The estimation model for V_{85} was obtained by means of a multiple regression for the $V_{85normal}$ (dependent variable) and the following independent variables (predictors):

- *curvature* (denoted by the term $1/R$) has been obtained as the inverse of radius;

Table 2. Data set processing

Num. veh.	Veh. type	DIR	$T1$ [sec]		$T2$ [sec]		$\Delta T=(T2-T1)$ [sec]	Fundamental Xi [m]	Car Speed $(\Delta T \cdot 3.6)/(X_i/25)$ [km/h]
			sec	1/25 sec	sec	1/25 sec			
1	Car	N	827	14	828	1	11.75	21.47	161.0
2	Car	N	55	2	55	14	12.00	21.47	161.0
3	Car	N	107	22	108	9	12.00	21.47	161.0
4	Car	S	842	1	842	12	11.00	19.20	157.1
5	Car	N	645	1	645	14	12.75	21.47	148.6
6	Car	N	410	17	411	5	12.75	21.47	148.6
7	Car	N	812	13	813	1	13.00	21.47	148.6
...	...	...	...	...	...	...	...	...	
...	...	...	...	...	...	...	...	...	
$n-2$	Car	S	335	19	336	14	20	19.20	86.4
$n-1$	Car	S	157	7	158	3	21	19.20	82.3
N	Car	S	644	4	645	0	21	19.20	82.3

Table 3. Observed V_{85} and calculated V_{85} using normal distribution.

Section location [km/h]	$V_{average}$ [km/h]	St. Dev. [km/h]	V_{85} calculated using Equation (1) [km/h]	V_{85} observed [km/h]
246.000	122.7	22.20	145.8	147.6
236.000	124.5	21.00	146.3	145.3
236.600	125.9	21.97	148.7	146.7
207.000	124.0	20.70	145.5	147.3
205.000	105.6	17.28	123.6	124.6
205.000	107.3	17.98	126.0	124.7
205.200	109.0	18.00	127.7	124.1
243.200	122.5	18.09	141.3	140.9
195.700	110.0	19.20	130.0	130.1
209.500	124.3	18.52	143.6	143.0
204.500	107.9	18.60	127.2	128.5
204.600	98.69	17.23	116.6	117.9
289.400	118.5	15.85	135.0	132.7
289.400	113.0	18.62	132.4	132.3
277.000	104.0	14.9	119.5	119.7

- *longitudinal grade* (denoted by the term $|i|$) has been taken at its absolute value because there is low variation in relation to 'upgrade' and 'downgrade' conditions, and is particularly weak on the tangent segments;
- *tortuousness* (denoted by the term $\sum_i \alpha_i/2$ and measured in grad/km) characterized by the form represented in Fig. 2 was introduced in order to take into account the ways drivers approach the element where their speed was measured:

In short, this term differentiates between different situations, as in the example given in Fig. 2 where the 'survey stations' share the same conditions (same length, same section width, same degree of slope etc.), but are preceded and succeeded by different degrees of tortuousness. Two attempts were made to choose the dependent variable. In the first attempt, we used $V_{85observed}$ while in the second we used $V_{85normal}$. The best results (though only slightly) were obtained at the second attempt; for this reason, $V_{85normal}$ was used as the dependent variable. This variable is very similar to the CCR (curvature change ratio) and was calculated 1.5 km before the survey section and 0.5 km after the survey section.

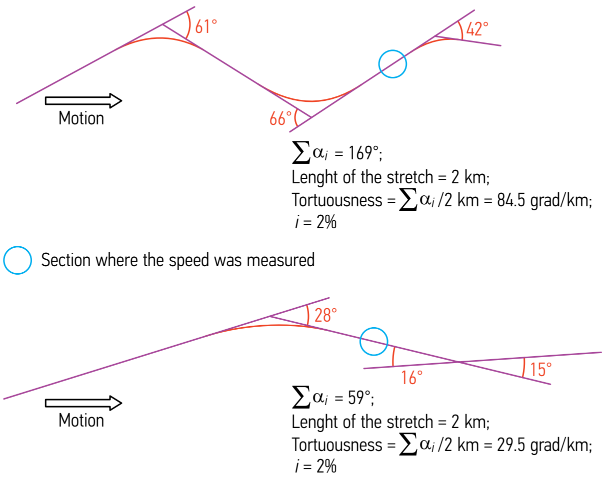

Fig. 2. Comparison between two different approaches to the section

The result obtained from the multiple regression is the following:

$$V_{85} = 154.8 - 2015 \cdot (1/R) - 0.42 \cdot \left(\sum_i \alpha_i/2 \right) - 4.2 \cdot |i|. \quad (2)$$

The coefficient R^2 is equal to 0.94, which confirms the strong relationship between the three independent variables and V_{85}. Moreover, the 't-student' test, carried out in order to control the significance of the variables (Table 4) used in the regression, confirmed the validity of model (2). A comparison was made between the evaluation results of the proposed model's ability to simulate the observed V_{85}. Table 5 shows the compared results.

Table 4. Result of the 't-student' test

	Coefficient	Standard deviation	t-student	Significance
Constant	154.8	2.021	76.58	0.000
$1/R$	2015	789.89	–2.55	0.027
$\sum_i \alpha_i/2$	0.42	0.107	–3.58	0.004
$\|i\|$	4.2	0.576	–7.35	0.000

Table 5. Comparison between 'observed V_{85}' and 'normal V_{85}'

Section location [km]	$V_{85calculated}$ obtained with model (2) [km/h]	$V_{85normal}$ obtained with eq. (1) [km/h]	Residual between $V_{85normal}$ and $V_{85calculated}$ [%]
246.000	144.4	145.8	1.0
236.000	148.6	146.3	1.5
236.600	146.5	148.7	1.5
207.000	143.5	145.5	1.4
205.000	126.4	123.6	2.2
205.000	125.9	126.0	0.1
205.200	128.0	127.7	0.2
243.200	143.6	141.3	1.6
195.700	126.5	130.0	2.8
209.500	143.9	143.6	0.2
204.500	121.6	127.2	4.6
204.600	118.9	116.6	1.9
289.400	135.7	135.0	0.5
289.400	133.0	132.4	0.5
277.000	123.6	119.5	3.3

With the help of model (2), some 'complex' assessments were designed and carried out (i.e. measurements on more than one element of the road alignment) on an approximately 20 km stretch of the A3 freeway. The characteristics of the stretch examined are shown in Table 6. The stretch analyzed was subdivided into 10 groups, so as to obtain sub-stretches of approximately 2 km made up of different elements of the alignment. The groups were formed in such a way that there were at least two different alignment features for each group.

Table 6. 't-student' test, model (2)

Group	Initial distance	Final distance	Curvature (1/m)	Slope [%]	Length of the group [m]	Tortuousness of the group [grad/km]	V_{85} calculated with model (2)	Number of crashes observed	Total crashes in the group	$V_{85average}$ in the group [km/h]
1	265.160	266.361	0.00000	5.0			128	1	10	127
	266.361	267.119	0.00065	5.0	1959	14.5	126	9		
2	267.119	267.410	0.00000	5.0			125	1	10	130
	267.410	267.860	0.00058	4.0			128	3		
	267.860	268.233	0.00000	3.3			132	2		
	268.233	268.461	0.00106	3.3			130	3		
	268.461	268.521	0.00000	3.3			132	0		
	268.521	268.703	0.00143	3.3			129	0		
	268.703	269.104	0.00000	3.3	1985	22.0	132	1		
3	269.104	269.762	0.00143	4.5			122	10	23	123
	269.762	271.058	0.00000	4.4	1954	27.4	125	13		
4	271.058	271.310	0.00108	2.5			139	0	6	140
	271.310	273.010	0.00000	2.5	1952	8.0	141	6		
5	273.010	273.856	0.00103	3.0			130	2	8	131
	273.856	274.966	0.00000	3.0	1956	25	132	6		
6	274.966	275.710	0.00036	2.9			119	3	32	116
	275.710	276.094	0.00000	3.8			116	7		
	276.094	276.622	0.00182	3.8			112	6		
	276.622	276.916	0.00000	3.8	1950	55	116	16		
7	276.916	277.187	0.00313	3.4			94	24	71	97
	277.187	277.297	0.00000	3.4			100	2		
	277.297	277.636	0.00333	3.4			94	10		
	277.636	277.956	0.00000	3.4			100	2		
	277.956	278.304	0.00167	3.4			97	16		
	278.304	278.524	0.00000	3.4			100	10		
	278.524	278.889	0.00208	3.4	1973	96	96	7		
8	278.889	279.279	0.00000	3.3			116	9	33	116
	279.279	279.384	0.00095	3.3			114	1		
	279.384	279.603	0.00000	3.3			116	3		
	279.603	279.863	0.00000	3.3			116	1		
	279.863	280.136	0.00000	3.3			116	16		
	280.136	280.466	0.00000	3.3			116	1		
	280.466	280.900	0.00000	3.3	2011	60	116	2		
9	280.900	281.240	0.00154	3.1			110	2	32	111
	281.236	281.680	0.00000	3.1			113	1		
	281.676	281.996	0.00143	3.1			110	2		
	281.996	282.250	0.00143	3.1			110	7		
	282.252	282.940	0.00270	3.1	2040	67	108	20		
10	282.940	283.358	0.00270	4.0			100	28	51	103
	283.358	283.408	0.00000	4.0			105	2		
	283.408	283.663	0.00172	4.0			102	14		
	283.663	284.153	0.00161	4.0			102	5		
	284.153	284.323	0.00000	4.0			105	0		
	284.323	284.407	0.00286	4.0			99	2		
	284.407	284.537	0.00000	4.0			105	0		
	284.537	284.667	0.00200	4.0			101	0		
	284.667	284.944	0.00000	4.0	2004	78	105	0		

Then, all the variables necessary to calculate V_{85} were calculated for each group. In addition, the last two columns (Table 6) show for each group $V_{85average}$ and the number of crashes (Prentkovskis *et al.* 2010) for the interval between 31/10/2008 and 31/10/2009 respectively. Two situations are immediately clear:

- the groups with the most crashes have higher tortuousness figures (see Fig. 3);
- in the groups with a $V_{85average}$ higher than 130 km/h the number of crashes is low while in groups where $V_{85average}$ is lower than 130 km/h, the number of crashes is higher.

This second result, which seems paradoxical in some ways, highlights a very interesting aspect of freeway traffic. In fact, the user in this type of traffic wishes to maintain an average speed close to 130 km/h (Dell'Acqua *et al.* 2011a). This is possible only in certain particularly favorable geometric conditions. In less favorable conditions, in cases where the degree of tortuousness, slope and curvature are higher, the user must reduce the speed. In many cases, however, the user changes speed in a way which is not appropriate to the geometric conditions and so drives on the limit, thus naturally increasing the probability of crashes. This becomes even more critical when the user passes through two 'groups' characterized by a $V_{85average}$ difference greater than 10 km/h (Dell'Acqua *et al.* 2011b). In this regard, model (3) was constructed using linear regression (3) between $V_{85average}$ and the number of crashes in the different groups (Fig. 4):

$$N.Crashes = -1.516 \cdot V_{85average} + 208.62; \quad R^2 = 0.92. \quad (3)$$

The significance value of model (3) is shown in Table 7. In addition, Table 8 and Fig. 5 show a correlation between the difference in velocity ($DV_{85average}$) between subsequent groups and the difference in the number of crashes (DN) between subsequent groups.

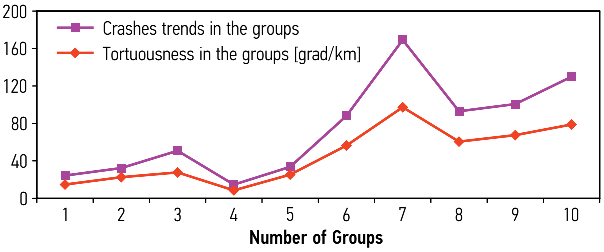

Fig. 3. Crashes related to tortuousness

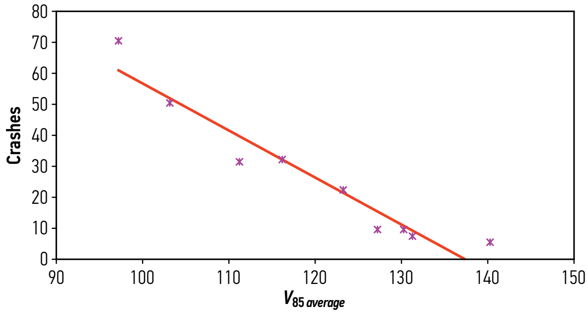

Fig. 4. Relationship between $V_{85average}$ and the number of crashes

Table 7. 't-student' test, model (3)

	Coefficient	Standard Deviation	t-student	Significance
Constant	208.62	18.29	11.40	< 0.001
$V_{85average}$	–1.516	0.152	–9.95	< 0.001

Table 8. Relationship between *DV* and *DN*

Group	$V_{85average}$	Number of crashes in the group	$DV_{85average}$, speed difference between group *i* and group *i*+1) (absolute value)	*DN*, crashes difference between group *i* and group *i*+1 (absolute value)
1	127.6	10	...	...
2	130.1	10	2.5	0
3	123.8	23	6.3	13
4	140.1	6	16.3	17
5	131.3	8	8.8	2
6	116.2	32	15.1	24
7	97.8	71	18.4	39
8	116.7	33	18.9	38
9	111.9	32	4.8	1
10	103.1	51	8.8	19

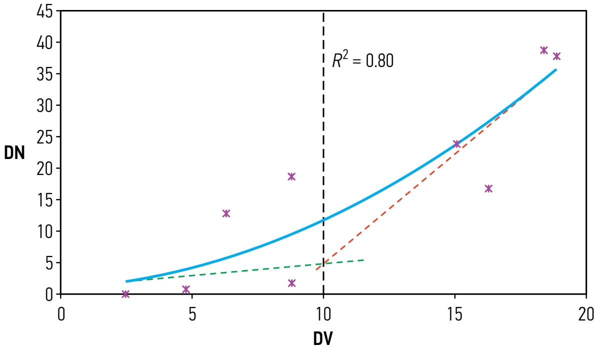

Fig. 5. Relationship between $DV_{85average}$ and *DN*

The higher crashes rate is found in areas with group whose V_{85} average difference is greater than 10 km/h. In particular, in Fig. 5 we observe that the lines that support the curve show two different trends: low correlation with a *DV* less than 10 km/h (with $R^2 = 0.33$) and high correlation with a *DV* greater than 10 km/h (with $R^2 = 0.71$).

6. Results and Conclusions

As demonstrated, the variables that significantly affect the V_{85} are 'curvature', 'longitudinal grade' and 'tortuousness'. The last term was introduced in order to take into account the ways drivers approach the element where their speed was measured. This term differentiates between different situations, as in the example given in

Fig. 2, where the 'survey stations' share the same conditions (same length, the same section width, same degree of slope etc.), but are preceded and succeeded by different degrees of tortuousness. The resulting model (2) showed good reliability at a local level. In fact, the maximum residual found in the experimental tests was within 5%. Moreover, the results obtained by applying the model to a stretch of highway of about 20 km, have highlighted some particular aspects of motorway traffic. In particular, using the procedure illustrated, it has been possible to identify some particular 'black spots' due to the poor design co-ordination of the alignment, positioned between consecutive stretches (for approximately 2 km), with a difference in terms of $V_{85average}$ greater than 10 km/h.

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