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Motorway Speed Management in Southern Italy

Gianluca Dell'Acqua[a,*], Mario De Luca[a], Raffaele Mauro[b], Renato Lamberti[a]

[a] *University of Napoli Federico II. Via Claudio 21; 80125 Napoli. Italy.*
[b]*University of Trento, Via Mesiano 77; 38123 Trento, Italy.*

Abstract

Comparing operating speed (V_{85}) with the theoretical design speeds makes many of the assessments fundamental to correct design more effective. In technical literature various models for estimatingV_{85} are present but they cannot be extended to motorways without risking substantial approximation. This study proposes a model for estimating V_{85} on motorways. In addition, it proposes a second model making it possible to estimate free flow speed (FFS) in various traffic conditions. This could be very useful for Level of Service studies on motorways.

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1. Introduction and literature Review

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). Speeding is a dominant cause of accidents in road transport. In order to improve safety, this is not the only element of the road transport system that should be considered (Török, 2011).

Many researchers have addressed driver speed behavior to identify all possible factors that may affect safety conditions during travel. These factors can be directly linked to personal choice, vehicle state, or the infrastructure and its environmental features. In the scientific literature there are many operating speed models for behavior on tangents and curves. The operating speed models set out in the literature generally predict a mean value of V_{85} (85^{th} percentile of speed distribution) at each geometric element, or a speed value for a given roadway section. The number of operating speed prediction models on tangents set out in the literature is generally lower than on circular elements because driver speed behavior is more complex to analyze. In fact, users have more freedom driving on tangent segments than on circular elements, and therefore the variables that can correctly explain the phenomenon are very numerous. Polus et al. (2000) developed, for example, a model to predict operating speeds on tangent segments. The sites were divided into four groups based on the 28 tangent lengths and the preceding and subsequent radius of the horizontal curves. Ordinary-least-square (OLS) models were developed for each tangent group. The model introduced one independent variable i.e., the average radius

* Corresponding author. *E-mail address*: gianluca.dellacqua@unina.it.

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of the horizontal curves preceding and following the tangent. The regression equation was recommended for segments with a curve radius of less than 820 ft (270.6 m) and a tangent length of less than 500 ft (165 m). Later, Fitzpatrick et al. (2003) collected speed and geometric data at 78 sites, and speed models for five different highway classes were developed. Except for the posted speed limit and access density, no other roadway characteristics were related to the operating speeds. Several empirical studies also exist in the literature relating to driver behavior on the circular curve as well as on entering and leaving it. In the first case, for example, some studies analyzed the vehicle's real movement trajectory in terms of the laws of geometry of movement and behavior of the vehicle under real traffic conditions, using software to monitor the steering path, Dragčević et al. (2008). In the second case a number of researchers have analyzed deceleration and acceleration motion in the transition zones.

Some studies have shown how acceleration and deceleration actions occurred only on segments of tangent and a constant speed was subsequently maintained by drivers on the circular elements (Fitzpatrick, Collins 2000; Ottesen, Krammes 2000). For example, a complete speed profile was analyzed by Dell'Acqua and Russo (2010). By using an iterative process, they obtained a deceleration transition length divided into the approach tangent to the horizontal curve and the circular element, and an acceleration transition length divided into the departure tangent from the horizontal curve and the circular element. They subsequently calibrated the predictive speed models on the tangents and curves.

Almost all the studies found in the literature concern two–lane rural roads, but few refer to motorways, so this study aspires to address this lacuna. The research is survey-based, and takes into account various geometric conditions, making it possible to find the variables that influence V_{85} and the FFS (Free Flow Speed). The information obtained was used to construct the models to estimate V_{85} and FFS on motorways.

2. The 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 distance marker 195 km (Castrovillari -CS- exit) and 253 km (Cosenza North -CS- exit). The geometric variables measured in each section are shown in table 1.

Table 1. Organization of the data

Reading nr.	Date of reading	Distance [km]	Dir.	Slope [%]	Length of section [m]	Curvature [1/m]	Tortuousness *. ($\Sigma\alpha i/3$) [grad/km]	State of paving	Transverse slope [%]	Distance from motorway-exit [km]
1	21/03/03	246.000	N	-2.0	10.7	0.0000	5.3	Dry	2.5	2.5
2	14/04/03	236.000	S	1.0	10.7	0.0000	5.3	Dry	2.5	2.0
3	30/05/03	236.600	S	1.5	10.7	0.0000	5.3	Dry	2.5	2.6
4	05/06/03	207.000	N	-0.5	8.7	0.0000	23.7	Dry	2.5	1.5
5	11/06/03	205.000	N	4.5	8.7	0.0000	24.7	Dry	2.5	2.1
6	18/06/03	205.000	N	4.5	8.7	0.0000	26.0	Dry	2.6	2.1
7	18/06/03	205.200	N	-4.0	8.7	0.0000	26.0	Dry	2.4	1.9
8	27/06/03	243.200	N	-1.0	10.7	0.0012	12.0	Dry	5.0	2.0
9	20/02/04	195.700	N	3.5	8.7	0.0014	28.0	Dry	5.5	1.2
10	21/02/04	209.500	N	0.1	8.7	0.0010	22.0	Dry	6.0	1.4
11	22/02/04	204.500	S	-4.5	8.7	0.0029	22.0	Dry	7.0	2.6
12	28/02/04	204.600	N	4.5	8.7	0.0029	29.0	Dry	7.0	2.7

* The meaning of this variable is explained in paragraph 6

3. System for recording vehicle speed and flow

A survey station was placed at each section, (as indicated in table1) to record the flow and speeds of the vehicles passing within a time interval "T". The structure of the survey station is represented in figure1. It consists of a digital television camera connected to a portable PC that shows the images that it captures. The system is set up across a section of the road, as in figure 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 figure 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" (Xi) it is possible to obtain the speed of the vehicles along "fundamental1" 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). 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.

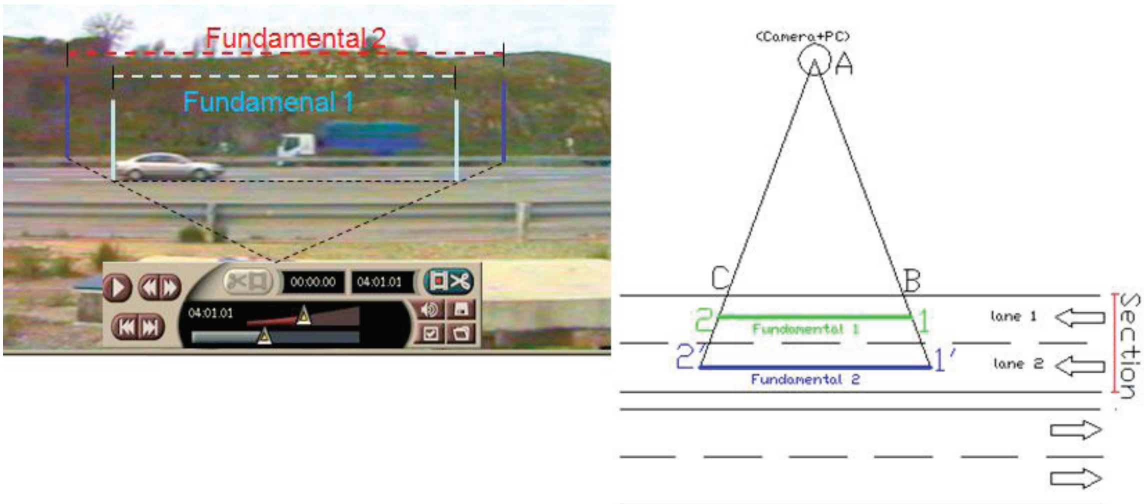

Figure 1. Structure of the survey station

4. Organization and processing the data

The data acquired from the survey station were organized in the sequence shown in table 2.

Then the number of vehicles per minute was converted into vehicles per hour and in order to account for the presence of vehicles other than cars, the volume (Vp, expressed in vph) was transformed into an equivalent "flow rate" (Qeq, expressed as pcphpl).

Table 2. Organization and processing of the data set

Veh. label	Veh. Type	T1 [sec.]	T1 [sec.]	Xi [m]	ΔT= (T1-T2)	Speed ΔT/ Xi [Km/h]	Gap label "i"	Nr Vehicles in the "i" Gap [vehic/min]	Average speed within the "i" gap (cars only) [km/h]
1	Lorry	9.18	10.19	23.85	26.00	82.56	1		
2	Car	21.12	22.10	23.85	23.00	93.33	1		
3	Car	36.9	37.03	23.85	19.00	112.97	1		
4	Car	38.23	39.12	26.29	14.00	169.01	1		
5	Lorry	49.17	50.17	23.85	25.00	85.86	1	5	125.10
6	Car	105.06	105.22	23.85	16.00	134.16	2		
7	Lorry	124.09	125.13	23.85	29.00	74.02	2		
8	Car	133.21	134.20	26.29	24.00	98.59	2		
9	Car	147.24	148.16	26.29	17.25	137.17	2		
10	Car	150.07	151.14	23.85	32.00	67.08	2	5	109.25

In order to obtain the Qeq it was necessary to determine the coefficient for each type of slope. The Et (Passenger–car equivalent) was determined starting from the hypothesis that if two different volumes, calculated at two different intervals give the same average speed, then the relative Qeq is the same. Therefore, once the intervals that satisfy this condition were identified, the coefficient of equivalence Et was determined, naturally discounting negative values and those less than 1 because of the obvious contrast with the physical significance of Et. Table 3 shows the Et values.

Table 3. Et Values.

Date	Distance	Slope [%]	**Et**
21/03/2003	246.000	-2.00	**1.70**
14/04/2003	236.800	1.00	**2.25**
30/05/2003	236.600	1.50	**1.85**
05/06/2003	207.000	0.50	**1.92**
11/06/2003	204.600	4.00	**3.70**
18/06/2003	204.000	4.00	**3.70**
18/06/2003	203.200	-4.00	**3.50**
27/06/2003	243.200	-1.00	**1.96**
20/02/2004	195.700	3.50	**3.50**
21/02/2004	209.500	0.10	**1.90**
22/02/2004	204.500	-4.50	**3.80**
28/02/2004	204.600	4.50	**3.70**

When the equivalent "Flow Rate Equivalent" (denoted by the acronym Qeq) and the average speed in each interval (denoted by the acronym Vm_1) were known, "Flow Rate" classes were constructed with 100vehic/h, and the average speeds for each class were calculated, represented by the acronym Vm_2.

Table 4. Average speed for each category

Class	**Qeq [pcphpl]**	**Vm_1 [km/h]**	**"i" Gap label**	**Vm_2 [km/h]**
1400-1300	1400	106.96	36	
	1380	120.87	10	113.91
1300-1200	1200	100.68	44	100.68
1200-1100	1140	115.61	6	115.61
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200-300	240	122.19	46	122.75

Using the data shown in table 4 and in particular using the Qeq and Vm_2 it was possible to construct flow diagrams for all 12 surveys and to establish the relationships that connect the Qeq with the Vm_2. Table 5 represents the equations that connect the Qeq and Vm_2 for each of the 12 flow diagrams. These equations were used in order to calculate the FFS given in the last column of table 5. The intercept of these equations represents the free flow speed (FFS). However, considering the paucity of points relating to low "Flow Rate" and questions concerning the linearity of the flow diagram, the FFS was assigned the speed value calculated as Qeq 300Veic/h. In this way the speed can be still thought of in conditions of free flow and the flow can be considered as linear.

5. Identifying the distribution for the average speeds

The distribution of the vehicles' average speeds is best represented by normal distribution. In order to verify whether the data used really approach normal distribution, an χ^2 test was carried out for each of the 12 surveys. In order to carry out this test, the speed data were organized into classes of 10 km/h each. Then, the absolute and theoretical frequencies were calculated, and last of all, χ^2 was calculated. Table 6 shows the results of the χ^2 test.

Table 5. FFS in the sections

Section Location [km]	Dir.	Slope [%]	Section width [m]	Curving [1/m]	Tortuous ness.	**T** [min.]	NrVe hicles in **T**	**Et**	Relationship between Qeq and Vm_2	FFS
246.000	N	-2.0	10.7	0.0000	5.3	60	656	2.00	$V_{average}$= - 0.0137*Qeq +134.31	**130.2**
236.000	S	1.0	10.7	0.0000	5.3	100	1210	2.25	$V_{average}$ = -0.0104*Qeq +134.74	**131.6**
236.600	S	1.5	10.7	0.0000	5.3	60	653	1.85	$V_{average}$ = -0.0117*Qeq +133.08	**130.0**
207.000	N	-0.5	8.7	0.0000	23.7	83	473	1.92	$V_{average}$ = -0.0073*Qeq + 129.29	**127.1**
205.000	N	4.5	8.7	0.0000	24.7	40	263	3.60	$V_{average}$ = -0.0003*Qeq + 105.53	**105.1**
205.000	N	4.5	8.7	0.0000	26.0	50	341	3.70	$V_{average}$ = -0.0054*Qeq + 106.47	**105.0**
205.200	N	-4.0	8.7	0.0000	26.0	56	400	3.50	$V_{average}$ = -0.0032*Qeq + 112.14	**111.1**
243.200	N	-1.0	10.7	0.0012	12.0	45	720	1.96	$V_{average}$ = -0.0030*Qeq + 126.01	**125.1**
195.700	N	3.5	8.7	0.0014	28.0	46	262	3.60	$V_{average}$ = -0.0069*Qeq + 117.60	**115.5**
209.500	N	0.1	8.7	0.0010	22.0	58	379	1.90	$V_{average}$ = -0.0035*Qeq + 128.41	**127.3**
204.500	S	-4.5	8.7	0.0029	22.0	45	187	3.80	$V_{average}$ = -0.0008*Qeq + 109.50	**109.2**
204.600	N	4.5	8.7	0.0029	29.0	45	187	3.70	$V_{average}$ = -0.0134*Qeq + 97.38	**93.3**

Table 6. Result of the χ^2 test

Date or reading	distance [km]	Total vehi cles	Nr of cars	Av. speed of cars [km/h]	S. Dev. [km/h]	Nr of classes	ν (degree of freedo m)	Fi (total absolute frequency - cars only)	fi (Tot. theoretical frequency - cars only)	ξ2 (Σ((Fi-fi)^2)/fi)	Check
21/03/03	246.000	656	512	122.7	22.20	14	11	512	510.67	11.56	Ok
14/04/03	236.000	1210	1002	124.5	21.00	14	11	1002	1000.80	24.14	Ok
30/05/03	236.600	653	515	125.9	21.97	14	11	515	513.80	26.88	Ok
05/06/03	207.000	473	305	124.0	20.70	14	11	305	302.10	19.79	Ok
11/06/03	205.000	263	192	105.6	17.28	11	8	192	191.60	7.02	Ok
18/06/03	205.000	341	281	107.3	17.98	12	9	281	280.72	23.50	Ok
18/06/03	205.200	400	318	109.0	18.00	13	10	318	317.81	14.14	Ok
27/06/03	243.200	720	589	122.5	18.09	14	11	589	588.94	18.68	Ok
20/02/04	195.700	262	195	110.0	19.20	10	7	195	192.8	6.58	Ok
21/02/04	209.500	379	306	124.3	18.52	13	10	306	304.89	12.73	Ok
22/02/04	204.500	187	116	107.9	18.60	9	6	116	114.4	3.39	Ok
28/02/04	204.600	187	168	98.69	17.23	9	6	168	166.23	8.33	Ok

Then, having established that normal distribution is well suited to the observed phenomenon, the V_{85} was calculated for each of the 12 surveys, using the expression:

$$V_{85} = V_{average} + 1.04 * St.dev. \tag{1}$$

The $V_{average}$, the standard deviation and the V_{85} determined using (1) are shown in table 7. The last column also shows the observed V_{85}, i.e., the speed that was exceeded in only 15% of the readings. The observed V_{85} and the V_{85} calculated using (1) are very close, which further confirms the suitability of normal distribution for the observed speeds.

Table 7. Observed V_{85} and V_{85} calculated using Normal Distribution

Section location [km/h]	$V_{average}$ [km/h]	S. Dev. [km/h]	observed V_{85} [km/h]	V_{85} Calculated using Normal Distribution [km/h]
246.000	122.7	22.20	147.6	145.8
236.000	124.5	21.00	145.3	146.3
236.600	125.9	21.97	146.7	149.0
207.000	124.0	20.70	147.3	145.5
205.000	105.6	17.28	124.6	123.5
205.000	107.3	17.98	124.7	126.0
205.200	109.0	18.00	124.1	127.7
243.200	122.5	18.09	140.9	141.3
195.700	110.0	19.20	130.1	129.9
209.500	124.3	18.52	143.0	143.4
204.500	107.9	18.60	128.5	127.2
204.600	98.69	17.23	117.9	117.0

6. Models for estimating V85

The estimation model for V_{85} was obtained by means of a multiple regression for the observed V_{85} (dependent variable) and the same variable indicated in table 1 (independent variable – predictors).

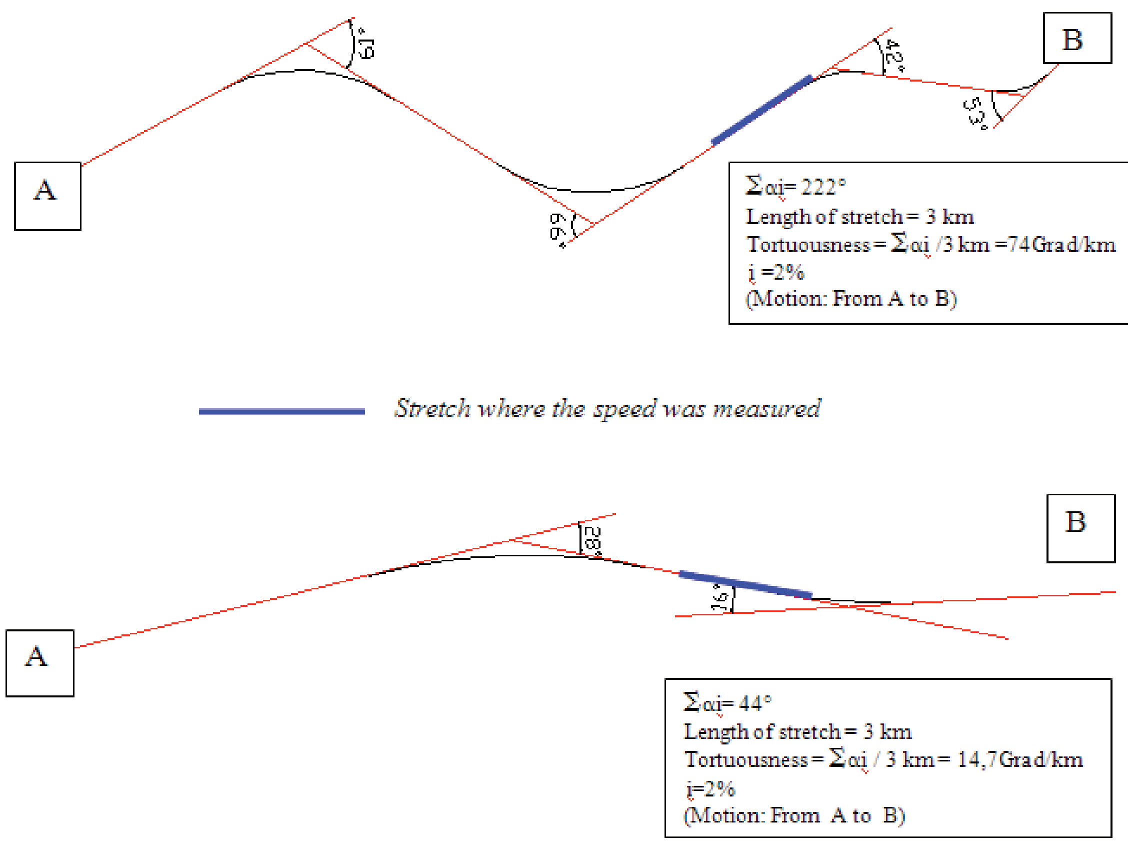

Figure 2. Comparison between two different approaches to the section

The most characteristic independent variables for V_{85} are indicated in table 8 as Var1, Var2, and Var3.

Var1: *Curvature* (denoted by the term 1/R) has been obtained as the inverse of radius;

Var2: *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.

Var3: *Tortuousness* (denoted by the term Σ_i αi/3 and measured in grad/km) characterized by the form represented in figure 2 and table 8 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 figure 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.

Table 8. Variables used for the multiple regression

Section Location [km]	Var 1 Longitudinal Slope [%]	Var 2 Curvature [1/m]	Var 3 Tortuousness. (Σαi/3) [grad/km]	observed **variation in dependent V_{85}** [km/h]
246.000	-2.0	0.0000	5.3	147.6
236.000	1.0	0.0000	5.3	145.3
236.600	1.5	0.0000	5.3	146.7
207.000	-0.5	0.0000	23.7	147.3
205.000	4.5	0.0000	24.7	124.6
205.000	4.5	0.0000	26.0	124.7
205.200	-4.0	0.0000	26.0	124.1
243.200	-1.0	0.0012	12.0	140.9
195.700	3.5	0.0014	28.0	130.1
209.500	0.1	0.0010	22.0	143.0
204.500	-4.5	0.0029	22.0	128.5
204.600	4.5	0.0029	29.0	117.9

The result obtained from the multiple regression is the following:

$$V_{85} = 155.13 - 1319 * \frac{1}{R} - 0.41 * \sum\left(\frac{\alpha i}{3}\right) - 4.1 * |i| \quad (2)$$

The coefficient ρ^2 is equal to 0.95, 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 variablesused in the regression, confirmed the validity of model (2) - see table 9.

Table 9. Results of "t-student" test

	Coefficient	standard Deviation	t-student	Significance
Constant	155.13	1.97	78.40	0.000
1/R	1319.63	842.89	-1.56	0.156
Σ_i αi/3	0.41	0.12	-3.53	0.008
|i|	4.10	0.66	-6.90	0.000

A comparison was made between the evaluation results of the proposed model (2)'s ability to simulate and the observed V_{85}. Table 10 and figure 3 show the compared results.

Table 10. Comparison of model (2) and observed and residual V_{85}

Date	Section Location [km]	calculated V_{85} using the (2) model [km/h]	observed V_{85} [km/]	V_{85} Calculated using normal distribution	Residual found between the "Observed V_{85}" and "Calculated V_{85}" using (2) model [%]
21/03/03	246.000	**144.8**	**147.6**	**145.8**	**1.2**
14/04/03	236.000	**148.9**	**145.3**	**146.3**	**0.7**
30/05/03	236.600	**146.8**	**146.7**	**149.0**	**1.6**
05/06/03	207.000	**143.4**	**147.3**	**145.2**	**1.4**
11/06/03	205.000	**126.6**	**124.6**	**123.5**	**0.9**
18/06/03	205.000	**126.0**	**124.7**	**126.0**	**1.0**
18/06/03	205.200	**128.1**	**124.1**	**127.7**	**2.9**
27/06/03	243.200	**144.6**	**140.9**	**141.3**	**0.3**
20/02/04	195.700	**127.4**	**130.1**	**129.4**	**0.5**
21/02/04	209.500	**144.4**	**143.0**	**144.3**	**0.9**
22/02/04	204.5 sud	**123.9**	**128.5**	**127.2**	**1.0**
23/02/04	204.5nord	**121.0**	**117.9**	**117.0**	**0.8**

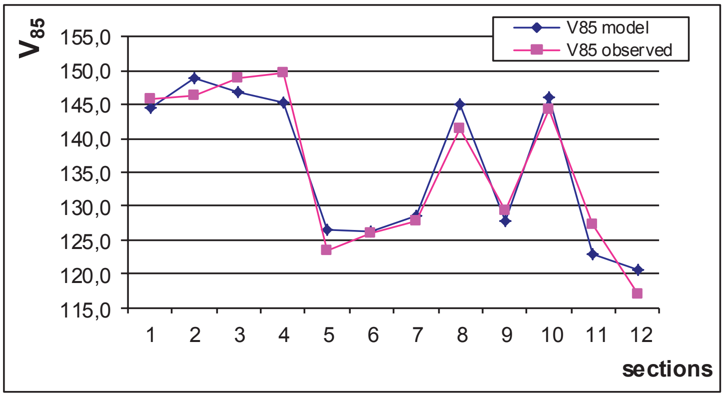

Figure 3. Comparison between the observed V_{85} and the V_{85} (2) models

7. Model for estimating the FFS

The model for estimating the FFS was obtained following the same procedures used in Section 6. Table 11 shows the variables used for the multiple regression, and the independent variables are given as Var1, Var2 and Var3. The result obtained with the multiple regression was the following:

$$FFS = 139.7 - 1703.3 * \frac{1}{R} - 0.47 * \sum(\frac{\alpha i}{3}) - 4.5 * |i| \quad (3)$$

The determination coefficient ρ^2 is 0.91. This result confirms the strong relationship between the three independent variables and the FFS. Moreover, the t-Student test carried out in order to assess the significance of the variables used in the regression confirmed the validity of relationship (3) (table 12).

A comparison was made between the results of the proposed model (3)'s ability to simulate and the FFS, which had been measured experimentally. Table 13 and figure 4 show the compared results.

Table 11. Variables used in the multiple regression

Section location [km]	Var1 Slope |i| [%]	Var 2 Curvature 1/R [1/m]	Var 3 Tortuousness. (Σαi/3) [grad/km]	**Dependent Variation of the FFS**
246.000	-2.0	0.0000	5.3	130.20
236.000	1.0	0.0000	5.3	131.62
236.600	1.5	0.0000	5.3	130.08
207.000	-0.5	0.0000	23.7	126.50
205.000	4.5	0.0000	24.7	105.12
205.000	4.5	0.0000	26.0	105.44
205.200	-4.0	0.0000	26.0	111.18
243.200	-1.0	0.0012	12.0	125.11
195.700	3.5	0.0014	28.0	115.53
209.500	0.1	0.0010	22.0	127.36
204.500	-4.5	0.0029	22.0	109.26
204.600	4.5	0.0029	29.0	93.36

Table 12. Result of the "t-student" test

	Coefficient	Standard Deviation	t-student	Significance
Constant	139.75	3.06	45.6	0.000
1/R	1703.38	1307.98	-1.3	0.229
Σ_i αi/3	0.470	0.18	-2.6	0.032
|i|	4.50	0.94	-4.8	0.01

Table 13. Residuals of Model (3)

Date	Section location [km]	**Observed FFS [km/]**	**FFS calculated using model (3)**	**Residual found between the "Observed FFS" and the "FFS calculated " using model (3) [%]**
21/03/03	246.000	130.2	128.2	1.5
14/04/03	236.000	131.6	132.8	0.9
30/05/03	236.600	130.0	130.5	0.3
05/06/03	207.000	126.5	126.4	0.1
11/06/03	205.000	105.1	107.8	2.5
18/06/03	205.000	105.4	107.2	1.7
18/06/03	205.200	111.1	109.5	1.5
27/06/03	243.200	125.1	127.6	1.9
21/03/03	246.000	130.2	128.2	1.5
14/04/03	236.000	131.6	132.8	0.9
30/05/03	236.600	130.0	130.5	0.3
05/06/03	207.000	126.5	126.4	0.1

8. Conclusion

This study illustrates how the speed of drivers on motorways varies systematically depending on a number of geometric variables. Observing the speed of drivers in these situations has thus led to the construction of models (2) and (3) which make it possible to estimate V_{85} and the FFS respectively. The variables that significantly influence V_{85} and the FFS are the curvature, the longitudinal slope and tortuousness. The last term was introduced in order to take into account the ways drivers approach the element where their speed is measured.

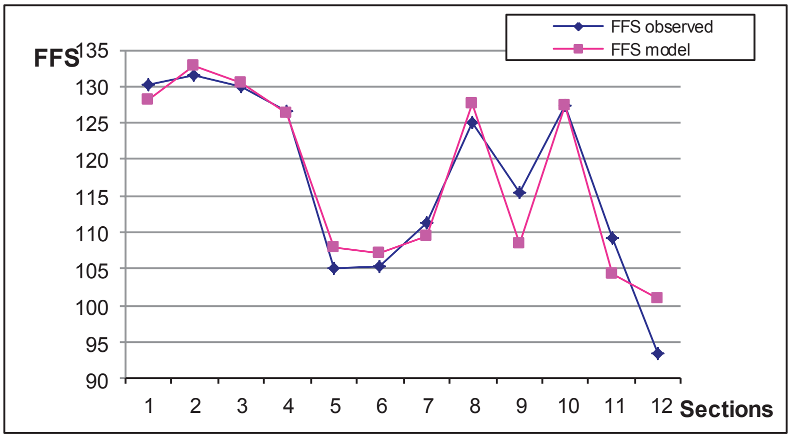

Figure 4. Comparison of the observed FFS and V_{85} models (2)

The two models proved to be reliable in the local context. In fact, the residual of V_{85} is less than 4% and the FFS is less than 8%. Thus, given the high level of reliability they show, the two models can be used for any kind of study and application for which these two variables need to be known. Work is ongoing to transfer the model to other roads. To this end, new experiments are being carried out on motorways with similar characteristics to the A3. Experimentation is in the development phase but the results are very encouraging.

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