APPLICATION OF DESIGN CONSISTENCY EVALUATION TOOLS FOR TWO-LANE RURAL ROADS: A CASE STUDY FROM ITALY

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ABSTRACT

The operating speed-profile model is an effective tool for the safety analysis of new and existing roads since it can be used for checking speed consistency violations. However, to effectively use the operating speed-profile it is necessary that it accurately predicts the speed along the road.
Therefore, the Design Consistency Module (DCM) of IHSDM (Interactive Highway Safety Design Model) and the recently developed model for the Italian context were applied to a real Italian two-lane rural road in rolling terrain with a complex alignment to evaluate their capability to fit the observed speeds. The comparison of the operating speed-profiles revealed that the DCM usually predicts operating speeds slightly higher than the Italian model, whereas the comparison between the predicted speeds and the observed speeds indicates that the Italian model fits slightly better the observed speeds on this type of road. All told, both the models predict quite well the observed speeds, even though there are cases in which the complex alignment strains the construction rules with the results that the predicted speed-profiles are not appropriate. The results of this case study are useful both to practitioners for a correct use of these models and to researchers for identifying the future research needs in an attempt to improve the capability of the models to predict speed-profiles that conform to the real speed observed.

INTRODUCTION

The consistency of a road alignment refers to the conformance of its geometry to driver expectancy. A horizontal curve that requires an excessive speed reduction with respect to the approaching speed to be travelled safely violates driver expectancy and consequently can be correlated with an increase in accident occurrence (*1*). The operating speed-profile model is an effective tool for the safety analysis of new and existing roads since it can be used precisely for checking design consistency violations. Moreover, it can be used for verifying the required sight distances, since through the speed evaluation it makes it possible to estimate the necessary sight distance at each point of the road. However, to effectively use the operating speed-profile it is necessary that it accurately predicts the speed along the road. Unfortunately, the existing operating speed-profile prediction models differ significantly from one model to the other. Therefore, the transferability of an operating speed-profile prediction model to a road not representative of the context for which the model was developed should be carefully evaluated.

The most widely used operating speed-profile model currently available is the Design Consistency Module (DCM) of the Interactive Highway Safety Design Model (IHSDM) developed by the Federal Highway Administration (*2*). The DCM is being used increasingly frequently also in Italy. Moreover, an operating speed-profile model was recently developed specifically for Italian two-lane rural roads (*3, 4*). Therefore, to evaluate the capability of these models to fit the observed speeds in an Italian context, both these models were applied to a real Italian two-lane rural road in rolling terrain with a complex alignment.

OBJECTIVES

The objective of the case study is to evaluate the operating speed-profiles generated by the Italian model and by the DCM on a rural roadway with a complex alignment which was never formally designed and that shows many features that are common to many Italian rural roads. The case study evaluated the capability of these models to fit the observed speeds, showing the differences between these two models, both in terms of speed prediction and in terms of construction rules. This case study was also used to evaluate the validity of some particular construction rules to be adopted by the Italian model that was never checked before. The results of this case study are useful to practitioners for a correct use of both models and, in particular, to correctly interpret their output on the basis of the specific characteristics of the alignment to be evaluated.

SUMMARY OF LITERATURE REVIEWS

Several speed-profile models for two-lane rural roads are currently available: the design speed-profile of the Italian standard (*5*) and that of the Swiss standard (*6*) from which the former derives; the operating speed-profiles developed by Lamm (*7*), by Krammes et al. (*8*), by Fitzpatrick et al. (*1*), by Marchionna and Perco (*3, 4*). This case study took into consideration the last two to evaluate their response to a real complex application on an Italian two-lane rural road.

The DCM is based on the operating speed-profile model proposed by Fitzpatrick et al. (*1*). This model takes into consideration the combination of horizontal and vertical alignments, using different equations to predict the operating speed on horizontal curves in function of the vertical alignment conditions or, if no horizontal curvature is present, to predict the operating speed on vertical curves along horizontal tangents. The model does not have a prediction equation for the desired speed on long tangents and a speed of 100 km/h is recommended. However, the DCM has the possibility to insert manually a different value of the desired speed. The speed-profile model includes acceleration and deceleration rates in function of the specific horizontal and vertical alignment conditions to adjust the speed prior to and departing from a curve. It should be noted that the operating speed prediction equations of this model are based on a curve sample that did not include very sharp curves (*1*). Consequently, the DCM predicts a speed equal to 60 km/h on all curves characterized by a radius below 80 meters. Effectively, one stated limitation of the DCM is that values for design features of the road analyzed outside the range of site selection criteria used to develop the DCM may result in a questionable output (*9*).

Marchionna and Perco developed an operating speed-profile model specifically for Italian two-lane rural roads (*3*). The model was developed on the basis of speed collected along roads with grades lower than 4%, therefore a limitation of the model is that it does not account for the vertical alignment. To improve the accuracy of the speed prediction this model considers the influence of the general character of the horizontal alignment on driver speed behaviour (*4*). The curvature change rate CCR is used in the model to describe this general character of the road. The model requires a preliminary dividing the road into road sections with a relatively uniform horizontal alignment called homogeneous sections. Using a plot relating the distance along the road to the sum of the absolute values of angular changes it is possible to select the homogeneous sections because they are characterized by an almost constant slope (*10*). The desired speed of each homogeneous section is predicted on the basis of its CCR index. The operating speed on curves is predicted using the equation corresponding to the CCR range within which falls the CCR index of the homogeneous section to which the curve belongs. Four different ranges, therefore four equations, are available. This structure allows the model to predict speed-profiles suitable for the specific alignment character of the road. Finally, the model uses prediction equations to estimate the acceleration and deceleration rates in function of the curve radius.

Donnell et al. (*9*) applied the DCM to two existing rural roads, an arterial and a collector road, and compared the operating speed-profile outputs to the speed observed along these roads. The arterial road had many similarities with the site selection criteria used to develop the DCM whereas some of the data along the collector road alignment were outside the range of these site selection criteria. The comparisons indicated that the DCM desired speed and the predicted operating speed closely matched the observed speeds on high-speed roadway (arterial), while the desired speed should be based on field data on lower-speed roadway (collector). The comparison between observed and predicted speeds on the collector roadway indicated that the difference was generally less than 8.0 km/h. However, to achieve these results, the desired speed had to come from observed speed data. Therefore, the authors recommended that users collect point speed data on a section of roadway at long tangent sections where speeds are not influenced by adjacent design features. The authors concluded that future research should be aimed at supplementing the existing DCM with an algorithm to evaluate two-lane rural highways that are different from those used to develop the current version of the DCM.

CASE STUDY

Road Characteristics

The road used for this case study is the national road S.S. n° 55, which links Trieste to Gorizia in the north-east of Italy. The road is 18 km long and traverses rolling terrain in a woody environment along the border with Slovenia. Along the road there are only two small built-up areas and few at-grade intersections with minor roads that are characterized by very low traffic volume. The road was built after the first world war and its alignment does not respect any rule that can ensure design consistency. This condition is common for many Italian rural roads.

Table 1 shows the geometric characteristics of the entire road and of the 6 homogeneous sections into which it was divided to apply the Italian model (*4*). Figure 1 is the plot relating the distance along the road to the sum of the absolute values of angular changes. This figure was used to identify the homogeneous road sections. The horizontal and vertical alignments were obtained from the Regional Cartographic Database integrated on the basis of some in-site inspections. The road is characterized by a complex horizontal alignment that includes 72 horizontal curves, some of which are very close to each other. The radii of these curves range from 35 to 10,000 meters. There are 14 sharp curves with a radius lower than 100 m and 8 large radius curves with a radius greater than 500 m. The road includes 73 tangent sections with a length that ranges from 13 to 1,096 meters. The roadway width ranges from 7 to 10 meters and the lane width ranges from 3.25 to 3.75 meters. The vertical alignment is gradual, with a grade that is always lower than 3.6%. It should be noted that this fact certainly does not enable the DCM to express to the full its potential since the speed is not affected by the vertical alignment. The posted speed limit is equal to 90 km/h along most of the road and only in correspondence of a few intersections and some very sharp curves is there a posted speed limit equal to 50 km/h.

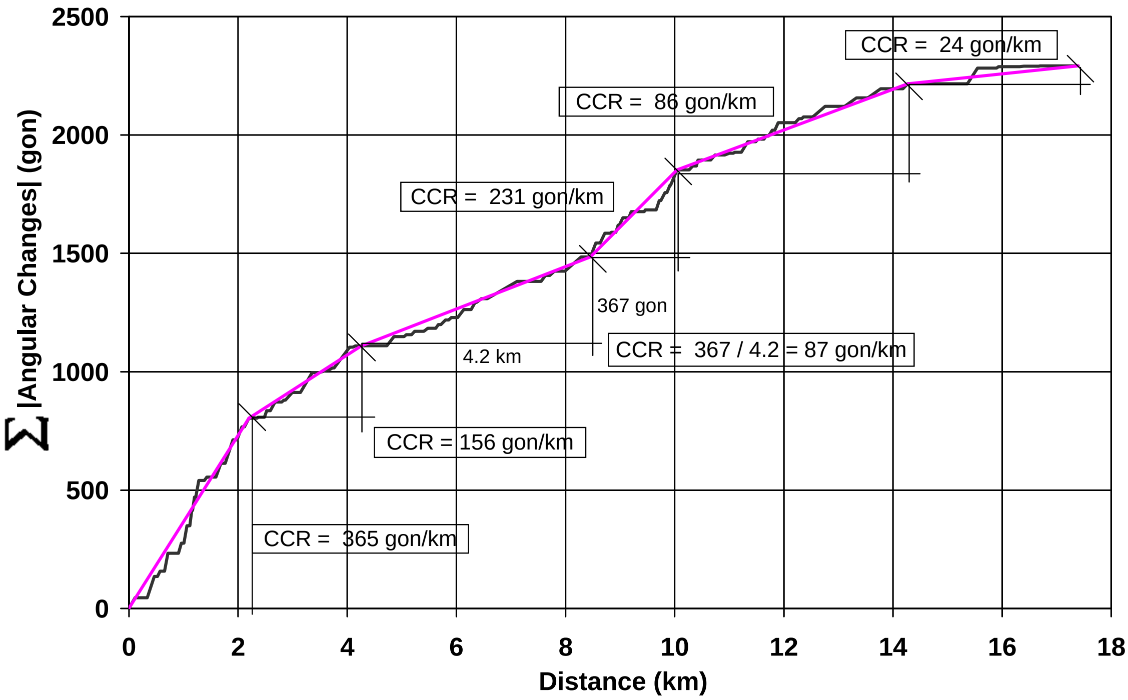

FIGURE 1 Homogeneous sections of the horizontal alignment

TABLE 1 Summary of Site Characteristics

Homogeneous Section		1	2	3	4	5	6	TOT
Length (m)		2,715.2	1,951.5	4,306.8	1,586.7	4,227.5	3,127.1	17,914.7
CCR (gon/km)		365.1	156.5	87.3	231.5	86.1	24.1	127.9
Number of elements		30	20	31	21	34	9	145
Horizontal Curves	Number of elements	15	10	15	11	17	4	72
	R_{min} (m)	35.0	100.0	160.0	92.0	72.0	175.0	35.0
	R_{av} (m)	156.0	333.0	926.0	131.0	315.0	1881.0	470.0
	R_{max} (m)	1,000.0	850	10,000.0	200.0	1,000.0	5,000.0	10,000.0
	L_{min} (m)	24.0	12.6	37.7	13.2	10.8	27.3	10.8
	L_{av} (m)	70.8	106.2	123.3	62.0	86.8	80.3	89.6
	L_{max} (m)	143.7	284.5	545.0	115.9	237.4	183.0	545.0
Tangents	Number of elements	15	10	16	10	17	5	73
	L_{min} (m)	13.2	25.7	22.7	13.1	42.3	268.3	13.1
	L_{av} (m)	110.2	88.9	153.5	90.4	161.9	561.2	157.0
	L_{max} (m)	311.4	152.0	439.6	238.2	404.4	1096.3	1096.3
Sag Vertical curves	Number of elements	3	2	3	0	5	1	14
	R_{min} (m)	1,000.0	2,041.0	1,770.0	-	1,299.0	6,000.0	1,000.0
	R_{av} (m)	1386.6	2565.0	3279.0	-	5394.4	-	3,721.3
	R_{max} (m)	2,143.0	3,089.0	4,217.0	-	9,882.0	6,000.0	9,882.0
Crest Vertical curves	Number of elements	3	1	2	0	2	0	8
	R_{min} (m)	1,365.0	9,358.0	11,570.0	-	1,504.0	-	1,365.0
	R_{av} (m)	1860.3	9358.0	11592.0	-	2433.0	6000.0	5,373.6
	R_{max} (m)	2,381.0	9,358.0	11,614.0	-	3,362.0	-	11,614.0
Grade	Number of elements	7	3	6	1	8	2	26
	G_{max} (%)	3.6	3.4	3.5	0.0	3.4	0.7	3.6
Speed Limit	PSL_{min} (km/h)	50	50	50	50	70	50	50
	PSL_{max} (km/h)	90	90	90	90	90	90	90

Speed-profiles construction rules

The construction rules of the speed-profiles were carefully compared since the greatest differences between the profiles are often due not so much to the predicted speeds, but rather to construction rules. Obviously, in this comparison it is important to remember that in the Italian model only the horizontal curves affect the speed, whereas in the DCM the vertical curves can also affect the speed when no horizontal curvature is present. It should be noted that this case study represented an opportunity to evaluate the construction rules for the following conditions D and F which should be adopted by the Italian model. The following lengths and speeds are used for the comparison. The lengths are to be understood as being calculated with the acceleration and deceleration rate adopted by the models.

L length of roadway available between the curve n and the curve n+1;
L_n length of curve n;
L_{n+1} length of curve n+1;
L_{LIM} length of roadway needed to accommodate full acceleration from the curve n to the desired speed and deceleration from the desired speed to the curve n+1;
L_{T1} length of roadway for acceleration from the curve n to the desired speed;
L_{T2} length of roadway for deceleration from the desired speed to the curve n+1;
L_{Td} length of roadway for deceleration from the curve n to the curve n+1;
L_{Ta} length of roadway for acceleration from the curve n to the curve n+1;
$L_{Td}*$ length of roadway for deceleration from V* to curve n+1;
$L_{Ta}*$ length of roadway for acceleration from curve n to V*;
V_n operating speed of the curve n;
V_{n+1} operating speed of the curve n+1;
$V*$ maximum achieved speed on roadway between curves;
V_{des} desired speed.

The following acceleration/deceleration conditions, shown in figure 2, were evaluated:

A. When the operating speed V_n is greater than operating speed V_{n+1} and the length of roadway L available between the curve n and the curve n+1 is greater than the critical length L_{LIM} the desired speed is reached and the construction rule is the same for both models (condition A of figure 2).

B. When the operating speed V_n is greater than operating speed V_{n+1} and the length of roadway L between the curve n and the curve n+1 is not sufficient to allow full acceleration to desired speed but is greater than the length to decelerate from the first to the second curve L_{Td} the construction rule is the same for both models (condition B of figure 2).

C. When the operating speed V_n is greater than operating speed V_{n+1} and the distance to decelerate from the curve n to curve n+1 is equal to the available distance ($L = L_{Td}$) the construction rule is the same for both models (condition C of figure 2).

D. When the operating speed V_n is greater than operating speed V_{n+1} and the distance to decelerate from the curve n to the curve n+1 is greater to the available distance ($L < L_{Td}$) the construction rules are different. The DCM fixes the predicted speeds along the curves and uses a greater deceleration rate than its standard rate to join them (condition D1 of figure 2). The Italian model fixes the speed only along the curve n+1 and calculates the distance L_{Td} necessary to decelerate from the speed V_n of curve n to the speed V_{n+1} of curve n+1. If this distance L_{Td} is lower than the distance available between curves L added to the length L_n of curve n, then the deceleration begins inside the curve n (condition D2a of figure 2). If the distance L_{Td} is greater than $L + L_n$, then the curve n is ignored and the process is repeated with the previous element (curve n-1 or tangent section) with the result that the construction could also fall back into a different condition (condition D2b of figure 2). Practically, the Italian model does not change the predicted deceleration rate and allows that a curve can be travelled at a variable speed, lower than that calculated by the prediction equation.

E. When the operating speed V_n is less than the operating speed V_{n+1} and the length of roadway L between the curve n and the curve n+1 is not sufficient to allow full acceleration to desired speed but is greater than the length to accelerate from the first to the second curve L_{Ta}, the rule is the same for both models (condition E of figure 2). It should be noted that in this case the model proposed by Fitpatrick (*1*) provides a rule different from that effectively used by the DCM. Obviously, if the length of roadway L available between the curve n and the curve n+1 is greater than the critical length L_{LIM} the desired speed is reached and the condition is analogous to that of condition A.

F. Finally, when the operating speed V_n is less than the operating speed V_{n+1} and the available distance L is lower than the distance L_{Ta} to accelerate from curve n to curve n+1, the rules are different. The DCM uses the standard acceleration rate to accelerate up to the curve n+1 that is travelled at the constant speed V'_{n+1} resulting from this acceleration even though this speed is lower than the speed V_{n+1} calculated for the curve n+1 using the prediction equations (condition F1 of figure 2). On the contrary, the Italian model calculates the distance L_{Ta} to accelerate from the speed V_n of curve n to the speed V_{n+1} of curve n+1. If this distance L_{Ta} is lower than the distance available between curves L added to the length L_{n+1} of curve n+1, than the acceleration ends inside the curve n+1 (condition F2a of figure 2). If the distance L_{Ta} is greater than L + L_{n+1}, than the curve n+1 is ignored and the process is repeated using the following element (curve n+2 or tangent section) with the result that the construction could also fall back into a different condition (condition F2b of figure 2). Practically, the Italian model allows that in this case too a curve can be travelled at a variable speed, lower than that calculated by the prediction equation.

The differences between the construction rules in the conditions D and F are significant and produce significant differences in the speed-profiles. It should be noted that in the condition D the rule of the Italian model has the defect of not considering the sight distance availability. In fact, if a driver can see a sharp curve beyond the next curve that he is about to negotiate, probably his deceleration behaviour also takes into account this sharp curve; but if he cannot see the sharp curve, he decelerates only up to the speed necessary to travel the next curve. The Italian model could show a correct profile in the first case, but it certainly does not show the correct profile in the second one. However, neither is the speed-profile of the DCM in the condition D reasonable if the distance available between the curves is very short, therefore the deceleration rate is very high. The Italian model would seem to be more representative of real driver behaviour in the condition F since the fact that the driver travels a circular curve, if this curve does not have a radius that limits his speed, is not a reason to induce the driver to stop the acceleration, travel the curve at a constant speed and, at the end of the curve, begin acceleration again according to the DCM. Moreover, the rate of this second acceleration is selected by the DCM on the basis of the radius of the last curve, therefore if this is a large radius curve the acceleration rate is low independently of the real travelling speed. Both these conditions are shown in figure 3 (between elements 105-110).

More generally, the application of the construction rules of both models to this complex alignment, characterized by sequences of different curves, with different radii and with short distances among them, evidenced the difficulty of adapting these rules to similar conditions. These sequences of curves are certainly not allowed by the actual standards and guidelines, but they are common along the existing roads whose alignments were often not formally designed on the basis of consistency rules. Therefore, this fact underlines the necessity to focus experimental studies on the speed behaviour along particular alignment conditions (in particular sequences of curves with very different radii and short distances between them) to implement more realistic construction rules.

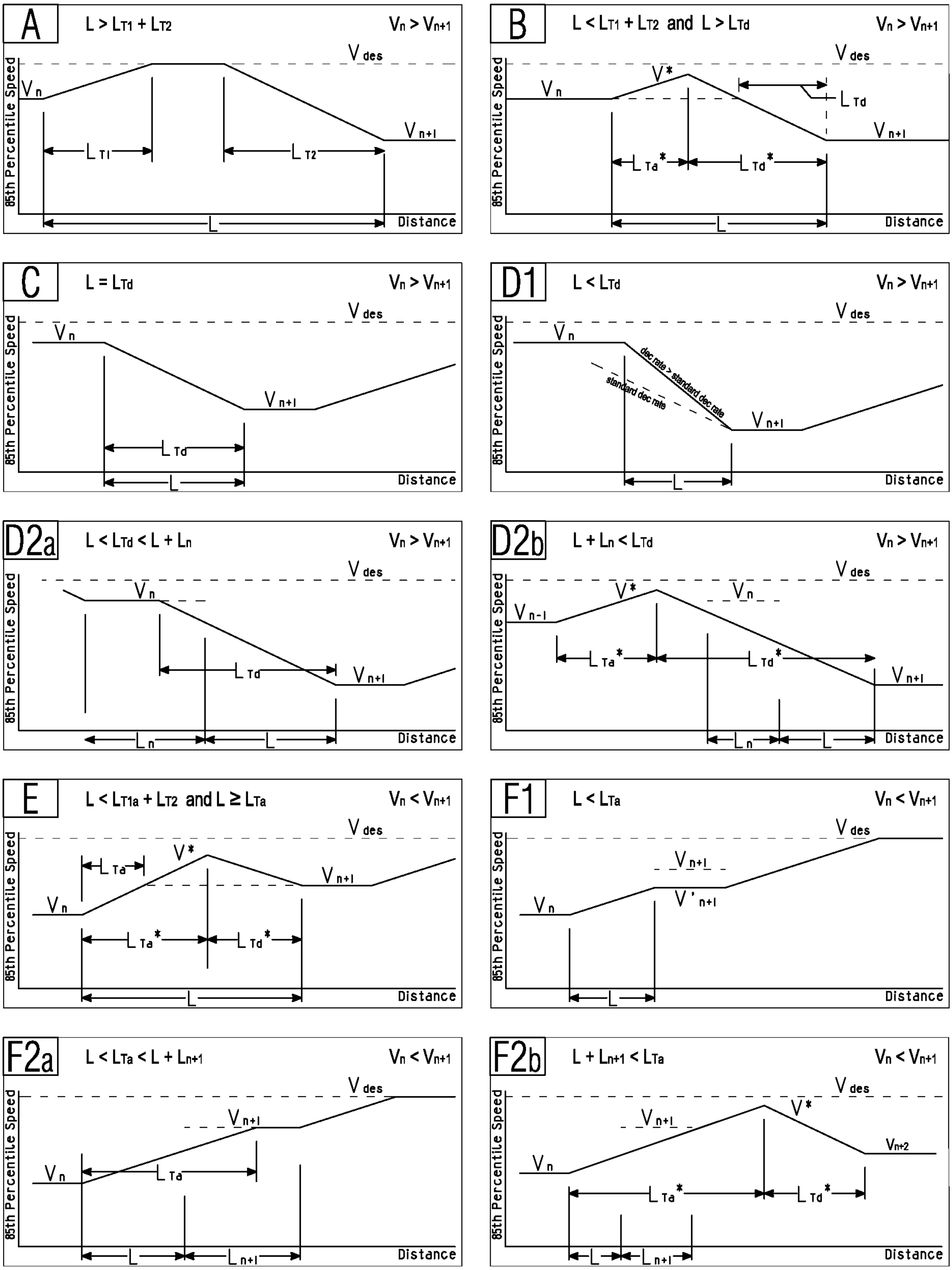

FIGURE 2 Acceleration and deceleration conditions

Speed-profiles comparison

The operating speed-profiles were predicted using the models for both directions (northbound direction: Trieste-Gorizia; southbound direction: Gorizia-Trieste). To apply the Italian model the desired speed was calculated for each of the six homogeneous sections of figure 1. For the DCM the suggested desired speed equal to 100 km/h was maintained along the whole road. Certainly, an expert user could manually modify the desired speed based on his experience or on specific speed measurements. However, in this study the choice to maintain the suggested desired speed was made since the objective was to apply the models in normal conditions, therefore considering a user not particularly expert and without speed measurements available.

The two operating speed-profiles were superimposed for both directions of the road and an analysis of the speed differences was performed. The results are similar for both directions and are shown in table 2. The analysis reveals that the DCM usually predicts operating speeds higher than the Italian model. Considering the circular curves, the speed V_{85US} predicted by the DCM is, on average, 6.3 km/h above the speed V_{85IT} predicted by the Italian model (the range is -11 km/h $\leq V_{85US} - V_{85IT} \leq$ +29 km/h). The minimum speed predicted by the Italian model is 42 km/h whereas the minimum speed predicted by the DCM is 60 km/h (along 6 curves) for the reason already mentioned above. Considering the tangent sections, the speed V_{85US} predicted by DCM is, on average, 4.8 km/h above the speed V_{85IT} predicted by the Italian model (the range is -12 km/h $\leq V_{85US} - V_{85IT} \leq$ +31 km/h). The DCM reaches the desired speed along 20 tangent sections whereas the Italian model does so along 15 tangent sections.

The final part of table 2 sums up the analysis of the differences between the speed V_{85US} predicted by the DCM and the speed V_{85IT} predicted by the Italian model. Considering that the models were applied to 144 curves (the analysis is performed in both directions, therefore the curves are 72 x 2 = 144), the DCM predicts speeds greater than the Italian model along 123 curves. The difference between the speeds is smaller than 5 km/h on 58 curves (about 40%) and smaller than 10 km/h on 124 curves (86%). Considering that the models were applied to 146 tangent sections (the analysis is performed in both directions, therefore the tangents are 73 x 2 = 146), along 121 tangent sections the DCM predicts speeds greater than the Italian model. The difference between the speeds is smaller than 5 km/h on 59 tangents (about 40%) and smaller than 10 km/h on 116 tangents (79%). The percentage both for curves and tangents are the same, showing a general tendency of the DCM to estimate higher speeds, not limited to a particular geometric feature (curve or tangent). All told, the analysis revealed that the average speed differences are quite small, both for curves and tangents, but on single elements can reach considerable values. However, these significant differences are due more to the differences in the construction rules than in the speed prediction equations. Figure 3 shows an example of these differences highlighting the cases D and F of figure 2.

Considering that both models were developed for checking speed consistency violations, it is interesting to compare the number and the locations of these violations using the same scale proposed by Lamm (7). The DCM raises 22 yellow flags ($10 \leq \Delta V_{85} < 20$ km/h) and 8 red flags ($\Delta V_{85} \geq 20$ km/h) whereas the Italian model raises 25 yellow flags and 5 red flags. It is particularly interesting that 20 inconsistencies are flagged by both the models (often with flags of different colours) whereas in the other cases the models flag different sequences of elements.

TABLE 2 Operating Speed Profiles Comparison

Section			1		2		3		4		5		6		Total	
Direction			NB	SB	NB	SB	NB	SB	NB	SB	NB	SB	NB	SB	NB	SB
Vdes IT			79.0		94.0		101.0		88.0		101.0		111.0		-	
Horizontal curves	V_{85US}	min	60.0	60.0	69.0	69.0	83.0	82.0	66.0	66.0	60.0	60.0	84.0	85.0	60.0	60.0
		mean	68.6	69.6	85.8	86.2	90.3	91.3	73.8	74.2	85.6	87.1	94.7	95	81.8	82.7
		max	100.0	100.0	95.0	99.0	96.0	100.0	87.0	84.0	96.0	100.0	100.0	100.0	100.0	100.0
	V_{85IT}	min	42.0	42.0	68.0	68.0	77.0	67.0	65.0	65.0	60.0	60.0	81.0	81.0	42.0	42.0
		mean	62.6	62.8	82.5	83	85.5	85.6	69.9	69.8	81.4	81.1	99.2	99.2	77.8	77.8
		max	80.0	80.0	94	94.9	101.0	101.0	76.0	76.0	95.9	92.5	111.0	111.0	111.0	111.0
	$\|V_{85US} - V_{85I}\|$	min	1.0	1.0	0.0	1.0	0.0	0.0	1.0	0.3	0.0	0.0	1.0	1.0	0.0	0.0
		mean	6.5	7.3	3.4	4.1	5.6	5.8	4.8	4.4	6.3	6.9	6.5	6.7	5.6	6.0
		max	20.0	20.0	7.0	7.0	8.0	8.0	11.0	8.0	12.3	29.3	11.0	11.0	20.0	29.3
	$V_{85US} - V_{85IT} > 0$	No.	13	13	7	8	12	13	9	10	13	15	2	2	56	61
		min	1.0	1.0	1.0	1.0	5.0	5.0	1.0	1.0	4.0	2.0	1.0	1.0	1.0	1.0
		mean	7.2	8.1	4.8	4.5	6.5	6.6	5.3	4.8	6.9	7.3	2.0	2.5	6.2	6.4
		max	20.0	20.0	7.0	7.0	8.0	8.0	11.0	8.0	12.3	29.3	3.0	4.0	20	29.3
	$V_{85US} - V_{85IT} < 0$	No.	2	2	1	2	2	1	2	1	3	1	2	2	12	9
		min	1.4	2.0	1.0	1.0	0.9	1.0	2.0	0.3	1.6	8.0	11.0	11.0	0.9	0.3
		mean	1.7	2.0	1.0	2.5	3.0	1.0	2.5	0.3	6.1	8.0	11.0	11.0	4.6	4.5
		max	2.0	2.0	1.0	4.0	5.0	1.0	3.0	0.3	10.0	8.0	11.0	11.0	11.0	11.0
Tangent Sections	V_{85US}	min	61.0	61.0	75.0	80.0	85.0	87.0	69.0	74.0	67.0	67.0	100.0	100.0	61.0	61.0
		mean	75.6	76.3	89.5	90.3	95.2	95.8	79.5	80.4	91.0	93.1	100.0	100.0	87.6	88.6
		max	100.0	100.0	95.0	99.0	100.0	100.0	92.0	94.0	100.0	100.0	100.0	100.0	100.0	100.0
	V_{85IT}	min	44.9	45.7	75.0	75.3	78.8	79.2	66.8	67.2	67.3	67.5	99.8	100.7	44.9	45.7
		mean	68.1	68.2	84.8	85.3	90.0	90.3	74.6	74.6	86.9	86.6	108.8	108.9	83.3	83.3
		max	80.0	80.0	92.2	90.3	101.0	101.0	83.6	84.2	99.5	99.3	111.0	111.0	111.0	111.0
	$\|V_{85US} - V_{85IT}\|$	min	0.8	0.2	0.0	0.3	0.3	0.4	0.7	1.1	0.3	0.5	0.2	0.7	0.0	0.2
		mean	7.5	8.1	4.7	5.1	5.5	5.7	5.0	5.8	6.3	6.8	8.8	8.9	6.2	6.6
		max	20.0	20.0	11.8	10.0	9.6	15.8	10.9	10.8	21.6	30.9	111.0	111.0	21.6	30.9
	$V_{85US} - V_{85IT} > 0$	No.	15	15	8	8	13	13	9	10	14	15	1	0	60	61
		min	0.8	0.2	2.4	3.3	0.3	2.7	0.7	1.1	0.5	0.7	0.2	-	0.2	0.2
		mean	7.5	8.1	5.9	6.3	6.5	6.9	5.4	5.8	6.4	7.6	0.2	-	6.4	7.1
		max	20.0	20.0	11.8	10.0	9.6	15.7	10.9	10.8	21.6	30.9	0.2	-	21.6	30.9
	$V_{85US} - V_{85IT} < 0$	No.	0	0	2	2	3	3	1	0	3	2	4	5	13	12
		min	-	-	0.0	0.3	1.0	0.4	0.7	-	0.3	0.5	11.0	0.7	0.0	0.3
		mean	-	-	0.1	0.4	1.0	0.8	0.7	-	6.1	0.9	11.0	8.9	5.1	4.1
		max	-	-	0.2	0.5	1.1	1.0	0.7	-	11.9	1.2	11.0	11.0	11.9	11.0

Summary of Speed differences								
	Tangent sections				Horizontal Curves			
	$V_{85US} - V_{85IT} \geq 0$		$V_{85US} - V_{85IT} < 0$		$V_{85US} - V_{85IT} \geq 0$		$V_{85US} - V_{85IT} < 0$	
direction	NB	SB	NB	SB	NB	SB	NB	SB
total	60	61	13	12	60	63	12	9
<5 km/h	22	22	7	8	20	24	8	6
<10 km/h	50	50	8	8	50	57	10	7
<15 km/h	56	56	13	12	54	58	12	9

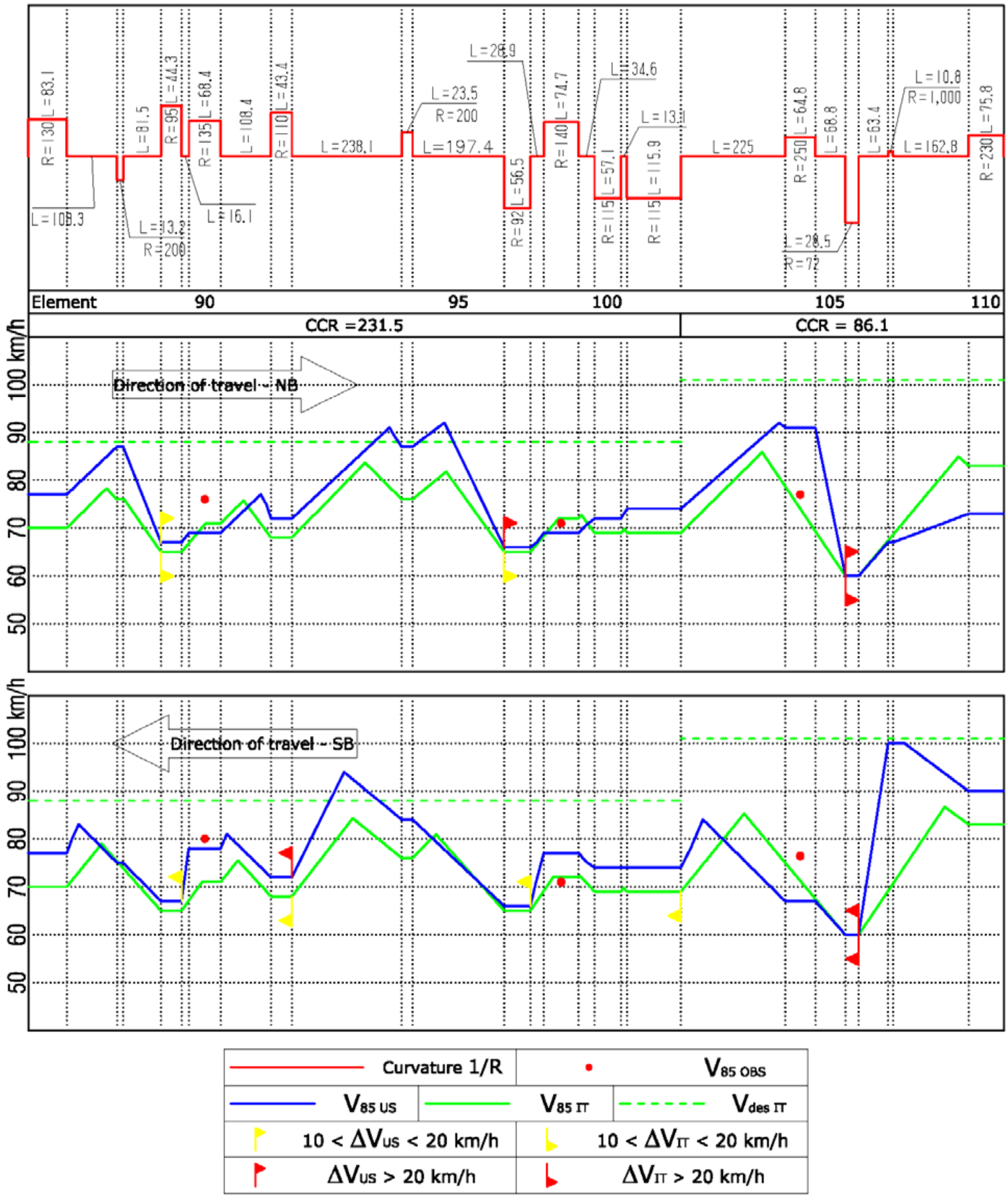

FIGURE 3 Comparison between the operating speed-profiles

Speed predicted vs. speed observed

To evaluate the capacity of the speed-profiles to predict the real operating speeds, speeds were collected on 17 sites (14 curves and 3 tangents) along the road using a laser speed-detection device that collects the speed of all vehicles, their length, direction, and time of passage. The equipment was placed perpendicular to the axis of the road outside the shoulder, and was always hidden from oncoming traffic in order to minimize the effects of its presence on driver speed behaviour. All the speed data were collected during daylight, at off-peak periods on a dry road. Vehicle headways of less than 5 seconds were removed, leaving only free-flow speeds in the database. Moreover, to avoid the presence of motorcycles or heavy vehicles in the database, vehicles shorter than 3 meters and longer than 6 m were also removed. To ensure an adequate sample size, it was verified that there were at least 100 valid passenger cars for each site.

Table 3 shows the operating speeds observed and predicted and table 4 shows the result of the comparison. The superimposition of the observed speed on the predicted speed-profiles of some sites is shown in figure 4. The Italian model predicts speeds greater than the speeds observed along 15 elements whereas the DCM does so along 23 elements; the Italian model predicts speeds lower than the speeds observed along 15 elements whereas the DCM does so along 10 elements. It should be noted that in 4 cases, the speed predicted by the Italian model is equal to the speed observed.

The average speed difference (ΔV_{85} = predicted speed V_{85PR} – observed speed V_{85OBS}) is -0.8 km/h for the Italian model and 3.2 km/h for the DCM, even though it is necessary to remember that this value is not really significant since the opposite signs of the differences can artificially reduce the average. To avoid this problem the average of the absolute values of the speed differences was calculated: the value is 3.6 km/h for the Italian model and 5.9 km/h for the DCM. Considering the Italian model, the average speed difference of the curves along which the speed is overestimated ($V_{85PR} - V_{85OBS} \geq 0$) is 2.4 km/h whereas the average speed difference of the curves along which the speed is underestimated ($V_{85PR} - V_{85OBS} < 0$) is -5.0 km/h. These values are respectively 6.4 km/h and -4.7 km/h for the DCM. All told, the Italian model tends to slightly underestimate the observed speeds whereas the DCM tends to overestimate it. Table 4 shows that the differences between the speeds predicted by the Italian model and the observed speed are lower than 5 km/h on 62% of the sites observed and lower than 10 km/h on 85% of the sites observed. These percentages are equal to 59% and 76% for the DCM.

The comparison between the predicted speeds and the observed speeds indicates that the Italian model fits the observed speeds slightly better. This happens, certainly, because the data used to develop the model were collected within the Italian context which is the same as the road analyzed. Moreover, these data were also collected along sharp curves of winding alignments. However, the fact that the structure of the model is optimized to predict speed for curves that belong to very different road alignments using different prediction equations certainly contributes to this result. Finally, considering that the alignment analyzed includes curves that do not fit the criteria developed for the data collection efforts of the DCM, it should be noted that the result is only slightly inferior to that of the Italian model.

TABLE 3 Operating Speeds Observed vs. Predicted

No. of Element	R (m)	L (m)	CCR (gon/km)	Direction	V_{85OBS}	V_{85US}	V_{85IT}	ΔV_{85US}	ΔV_{85IT}
3	∞	311.4	365.1	NB	73.4	92.0	79.0	18.6	5.6
				SB	72.9	87.0	78.0	14.1	5.1
6	93	131.8	365.1	NB	62.0	66.0	65.0	4.0	3.0
				SB	64.0	66.0	65.0	2.0	1.0
10	54	64.5	365.1	NB	56.2	60.0	54.0	3.8	-2.2
				SB	56.9	60.0	54.0	3.1	-2.9
11	∞	192.0	365.1	NB	73.1	70.7	68.7	-2.4	-4.4
				SB	73.1	69.2	72.7	-3.9	-0.4
24	100	91.3	365.1	NB	65.0	69.0	66.0	4.0	1.0
				SB	66.0	69.0	66.0	3.0	0.0
26	92	143.7	365.1	NB	65.0	66.0	65.0	1.0	0.0
				SB	62.0	66.0	65.0	4.0	3.0
28	100	86.0	365.1	NB	72.3	69.0	66.0	-3.3	-6.3
				SB	77.1	69.0	66.0	-8.1	-11.1
36	150	85.8	156.5	NB	73.0	75.0	76.0	2.0	3.0
				SB	75.3	81.0	76.0	5.7	0.7
40	260	131.1	156.5	NB	84.0	88.0	85.0	4.0	1.0
				SB	85.0	91.0	85.0	6.0	0.0
42	161	213.2	156.5	NB	73.0	83.0	77.0	10.0	4.0
				SB	80.0	83.0	77.0	3.0	-3.0
70	160	75.9	87.3	NB	83.0	83.0	77.0	0.0	-6.0
				SB	79.8	82.0	77.0	2.2	-2.8
74	476	545.0	87.3	NB	96.0	92.0	92.0	-4.0	-4.0
				SB	102.0	97.0	92.0	-5.0	-10.0
90	135	68.4	231.5	NB	76.0	69.0	71.0	-7.0	-5.0
				SB	80.0	78.0	71.0	-2.0	-9.0
98	140	74.7	231.5	NB	71.0	69.0	72.0	-2.0	1.0
				SB	72.0	77.0	72.0	5.0	0.0
104	250	64.8	86.1	NB	77.0	91.0	74.0	14.0	-3.0
				SB	76.4	67.0	71.3	-9.4	-5.1
125	∞	311.7	86.1	NB	82.0	93.8	88.7	11.8	6.7
				SB	87.0	98.0	90.4	11.0	3.4
132	375	214.2	86.1	NB	85.0	96.0	89.0	11.0	4.0
				SB	84.7	96.0	89.0	11.3	4.3

TABLE 4 Results of the Comparison between Operating Speeds Observed and Predicted

Speed difference			US	IT
$V_{85PR} - V_{85OBS} > 0$	Number of cases		23	15
$V_{85PR} - V_{85OBS} < 0$	Number of cases		10	15
$V_{85PR} - V_{85OBS} = 0$	Number of cases		1	4
$(V_{85PR} - V_{85OBS})$	km/h	min	-9.4	-11.1
		mean	3.2	-0.8
		max	18.6	6.7
$\lvert V_{85PR} - V_{85OBS} \rvert$	km/h	min	0.0	0.0
		mean	5.9	3.6
		max	18.6	11.1
$V_{85PR} - V_{85OBS} \geq 0$	km/h	min	0.0	0.0
		mean	6.4	2.4
		max	18.6	6.7
$V_{85PR} - V_{85OBS} < 0$	km/h	min	-2.0	-0.4
		mean	-4.7	-5.0
		max	-9.4	-11.1
$\lvert V_{85PR} - V_{85OBS} \rvert$	%	< 2.5 km/h	20.6	20.6
		< 5 km/h	58.8	61.8
		<7.5 km/h	67.6	79.5
		<10 km/h	76.5	85.3

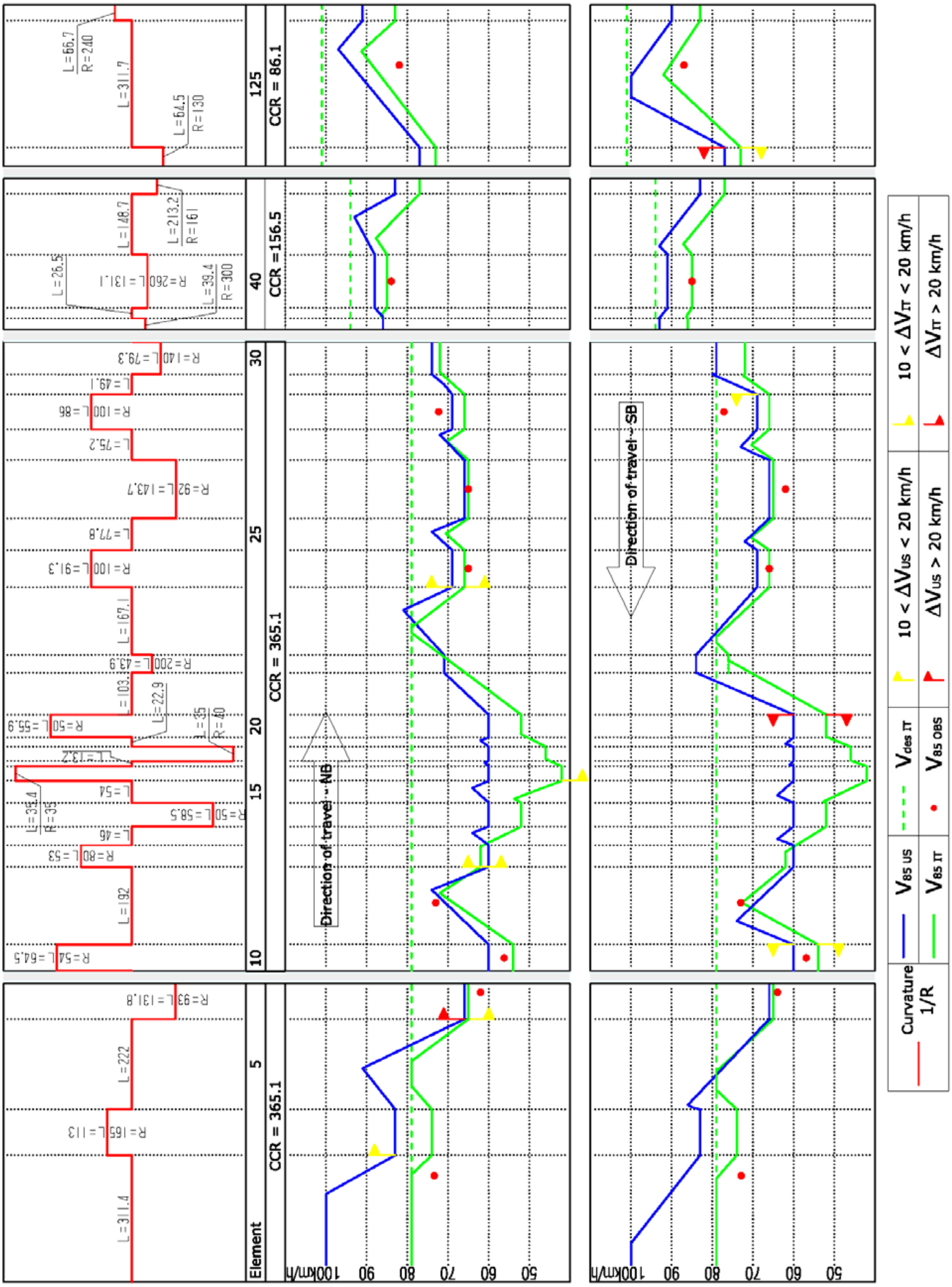

FIGURE 4 The operating speed-profiles with the observed speeds superimposed

CONCLUSIONS

The speed-profile model is an effective tool for the safety analysis of new and existing roads and its use is gradually becoming widespread in Italy too especially for the analysis of existing roads. However, to effectively use the operating speed-profile it is necessary that it accurately predicts the speed along the road. Therefore, the Design Consistency module of IHSDM and the recently developed model for the Italian context were applied to a real Italian two-lane rural road in rolling terrain with a complex alignment to evaluate their capability to fit the observed speeds.

The comparison of the operating speed-profiles revealed that the DCM usually predicts operating speeds slightly higher than the Italian model, whereas the comparison between the predicted speeds and the observed speeds indicates that the Italian model fits the observed speeds slightly better. This happens, certainly, because the Italian model was developed using data collected within the Italian context which is the same as the road analyzed. However, the structure of the Italian model, developed to predict speed-profiles along roads with different alignment characters, certainly contributes to this result. All told, both the models predict the observed speeds quite well, even though there are cases in which the complex alignment strains the construction rules with the result that the predicted speed-profiles are not appropriate. This fact underlines the necessity to focus experimental studies on speed behaviour along particular alignment conditions to implement more realistic construction rules.

Considering the specific Italian context, characterized by two-lane rural roads with very different alignment conditions, from winding alignments with many sharp curves to straight alignments with very long straight sections, the principal shortcoming encountered for the DCM is that it does not account for the general character of the alignment in the prediction of the desired speed and of the speed on curves. This entails a careful evaluation on the part of the user of the applicability of the DCM in function of the specific characteristics of the alignment.

On the other hand, the principal shortcoming of the Italian model is that it does not account for the vertical alignment conditions in the speed prediction. This would also entail a careful evaluation on the part of the user.

In conclusion, both the models show a reasonable prediction capability along the road analyzed but the case study evidenced the need on the part of the user to evaluate the results carefully in function of the specific characteristics of the alignment under evaluation. Finally, this case study was useful for identifying the future research needs in an attempt to improve the capability of the models to predict speed-profiles that conform to the real speeds observed.

REFERENCES

1. Fitzpatrick K., L. Elefteriadou, D. Harwood, J. Collins, J. McFadden, I. Anderson, R.A. Krammes, N. Irizarry, K. Parma, K. Bauer, K. Passetti. *Speed Prediction for Two-Lane Rural Highways*. Report FHWA-RD-99-171, FHWA U.S. Department of Transportation, 2000.
2. IHSDM Homepage. U.S. DOT, Federal Highway Administration. http://www.tfhrc.gov/safety/ihsdm/ihsdm.htm. Accessed January 21, 2009.
3. Marchionna A., P. Perco. Operating Speed-Profile Prediction Model for Two-Lane Rural Roads in the Italian Context. *Advances in Transportation Studies – An International Journal*, Vol. XIV April 2008, Rome, Italy, pp. 57-68.
4. Perco P.. Influence of the General Character of Horizontal Alignment on operating Speed of Two-Lane Rural Roads. *Transportation Research Record*, No.2075, TRB, National Research Council, Washington, D.C., 2008, pp. 18-23.
5. *Norme funzionali e geometriche per la costruzione delle strade*. D.M. 05.11.2001, Ministry of Infrastructures and Transportation, Rome, Italy, 2001.
6. *Schweizer Norm SN 640-080-b, Projektierung Grundlagen – Geschwindigkeit als Projektierungselement,* Vereinigung Schweizerrischer Strassenfachleute. Zurich, Swizerland, 1991.
7. Lamm R., Psarianos B., Mailaender T.. *Highway Design and Traffic Safety Engineering Handbook*. McGraw-Hill, United States, 1999.
8. Krammes R. A., R. Q. Brakett, M.A.Shaffer, J. L. Ottesen, I. B. Anderson, K. L. Fink, K. M. Collins, O. J. Pendleton, C. J. Messer. *Horizontal Alignment Design Consistency for Two-Lane Highways*. Report FHWA-RD-94-034, FHWA, U.S. Department of Transportation, 1995.
9. Donnel T.E., B.P. Stodart, F. Gross, K. Opiela. Appraisal of the Interactive Highway Safety Design Model's Crash Prediction and Design Consistency Module Results: Case Studies from Pennsylvania. *Journal of Transportation Engineering*, Vol. 135 No. 2, American Society of Civil Engineers , 2009, pp. 62-73.
10. *Richtlinien für die Anlage von Strassen: Linienführung RAS-L*. Forschungsgesellschaft für Strassen-und Verkehrswesen, Germany, 1995.