Comparative Safety Analysis of a Two-Lane Two-Way Major Highway, Using IHSDM and a Portuguese Procedure

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ABSTRACT

The Interactive Highway Safety Design Model (IHSDM) is a software tool for evaluating safety and operational effects of alternatives in highway projects, which is available through the US Federal Highway Administration (FHWA). IHSDM can be applied in the design of new highways and in the major redesign of existing highways. The software contains five modules, intended for the evaluation of measures describing relevant aspects of the expected safety and operational performance of a highway design. Three of these modules are potentially relevant for use outside the US: the Crash Prediction Module, the Design Consistency Module, and the Traffic Analysis Module.

A procedure for the detection of inconsistent horizontal curves in single carriageway rural roads of the National Road Network and the improvement of their safety records was developed at the National Laboratory of Civil Engineering (LNEC) for application in Portugal, using driver behaviour and safety data collected in the national context. The procedure may be applied automatically using the dedicated software PERVEL – Dangerous Curves Detection System.

Within the context of the redesign of a dangerous stretch of single carriageway two-lane highway in the mountainous area in the North of Portugal, operational and safety data were collected and used in the analysis of its safety performance. Both IHSDM and the Portuguese procedure were used in this analysis. This was due to the fact that speed profiles in PERVEL are calculated considering horizontal geometric characteristics only, hindering its direct application in roads in mountainous areas, whereas relevant IHSDM modules includes both horizontal and longitudinal profile characteristics. IHSDM is suited for application under North American traffic conditions, which forced the recalibration of particular parameters for its application at the relevant Portuguese road stretch.

In this paper a comparison is made between the results obtained using both procedures, in what concerns the detection of inconsistent horizontal curves and dangerous non-intersection sites. The main issues arising from the calibration of the crash prediction module to the Portuguese context are described.

INTRODUCTION

Horizontal road curves increase the difficulty in driver tasks, as compared to straight sections, contributing to a higher risk of lane departures that may lead to head-on collisions and collisions with roadside obstacles. For instance, during the five year period 2003-2007 more than 28% of the accidents registered in Portuguese single carriageway roads occurred on curves, resulting in more than 29% of the total number of fatal and serious injuries in that type of roads. These high numbers of accidents on curves correspond to an increase in the accident risk at curves, as well: Portuguese rural road links had an overall accident rate on curves that is almost 50% higher than on tangents (*1, 2*).

Visibility (how easy it is to perceive that there is a curve ahead and at what distance), readability (how easy it is for a driver to evaluate the curve geometry, in order to adopt an adequate behaviour) and skidding resistance (as resulting from friction coefficients and macrotexture) are some important characteristics that have significant impact in safety at curves (*3*). Roadside characteristics (especially the existence of dangerous obstacles in the vicinity of the carriageway) are also important, as regards run-off-the-road accident severity outcomes.

Curves on rural roads are geometric features that may generate visibility, tracking and vehicle stability problems that may contribute to violate drivers' expectancy. From a safety point of view, it is important to detect those curves where these driver expectancy violations may occur (the inconsistent road curves), in order to alert the unfamiliar drivers, or to improve road characteristics in the proximity of those curves. Several methods have been proposed to address this issue (*8* to *15*) and are briefly mentioned in the next chapter.

In this paper a comparison is made between the results obtained with the use of two such methods within the context of the redesign of a dangerous 43 km stretch of single carriageway two-lane road of the Portuguese National Road Network (NRN). Both, the Interactive Highway Safety Design Model (IHSDM), developed by FHWA, and the Dangerous Curves Detection System (PERVEL), developed at LNEC, were used in the safety analysis of this stretch of mountainous road. Speed profiles in PERVEL are calculated considering horizontal geometric characteristics only, whereas relevant IHSDM modules include both horizontal and longitudinal profile characteristics. On the other hand, IHSDM is suited for application under North American traffic conditions, which forced the recalibration of particular parameters for its application at the relevant Portuguese road stretch. However, several successful applications of IHSDM outside the scope of its area of development have been reported (*4* to *7*). As the analysed road is in a Portuguese mountainous area, and longitudinal profile characteristics affect traffic speed, it was decided to use both systems in the consistency analyses.

The main issues arising from the calibration of the crash prediction module to the Portuguese context are described, as well. Finally, main results from the simulation of operational consequences resulting from proposed speed management safety interventions are presented.

GEOMETRIC CONSISTENCY EVALUATION

In psychological studies, expectancy is the process by which the response of a person to a set of stimuli is defined according to a selection of concepts and ideas that he/she has learned previously. Expectancy is the tendency of a driver to react to a situation, an event or a set of information in a systematic way, based on his/her past experience. Geometric consistency is the agreement between the characteristics of the geometric design of a road and the unfamiliar driver's expectations (*8*).

Several methods for representing driver expectancy and for evaluating the design consistency of a road were developed by researchers. In some cases, geometric indices derived directly from the design characteristics of the road layout (*9* and *16*) are used; other methods require the estimation (objective or subjective) of driver workload (*8*, *16*, *11*, and *13*). However, the most used methods rely on selected parameters of the unimpeded speed distribution (usually the average or the 85th percentile are used), and on how they change from road section to road section (8, *16*, *17*, *10*, *11* and *12*). Their application requires the use of a procedure for estimating the unimpeded speed profile along the road. Unimpeded speeds are observed under very low traffic volumes.

In the evaluation of the design consistency of the analysed IP4 road stretch two methods based on unimpeded speed were used: IHSDM and PERVEL.

IHSDM is a suite of integrated computer programs for supporting decisions regarding geometrics design aspects of single carriageway roads, taking in consideration both operational – especially those related to traffic capacity – and safety (*9*). With this software it is possible to make quantitative comparisons of the expected accident frequency of alternative road designs. IHSDM, which is available from FHWA [*www.ihsdm.org*], may be used in the design of new roads and in the redesign of existing ones. The suite comprises six evaluation modules: the policy review, crash prediction, design consistency evaluation, traffic analysis, driver/vehicle and intersection review. Each module corresponds to a unique evaluation perspective and was designed to generate appropriate related operational and safety performance indicators.

The policy review and intersection review modules automate the process of checking road geometric design characteristics against relevant AASHTO design policy. The other four modules are especially suited for use under North American traffic conditions. However, their application under other traffic conditions is possible, provided adequate recalibration of selected relevant parameters is made. This is especially applicable to the traffic simulation model (based on TWOPAS) in the traffic analysis module and to the accident prediction model of the crash prediction module.

PERVEL is a computer program for the detection of dangerous horizontal curves, based on the consistency evaluation of the road's horizontal alignment (*2*). The program was developed at LNEC, and uses driver behaviour (speed) and accident prediction models for curves and tangents on Portuguese roads, to classify horizontal curves in five consistency classes. The practical application of the method involves several steps: the division of the road in curved and straight elements (respectively curves and tangents); the calculation of the unimpeded speed profiles of the road (one for each direction); the estimation of the increase in accident risk on each curve (as related to the expected accident risk if it was a tangent), which is used to calculate an inconsistency factor (FH); the calculation of the expected deceleration rate on drivers' approach to each curve; and the calculation of the consistency class for each curve, based on the calculated FH, the values of speed reduction and the expected deceleration rate. Criteria for this classification are summarized in Table 1.

TABLE 1 - Classification of Horizontal Curve Consistency (*2*)

Consistency Class *	**Speed Reduction**	**Deceleration**	**Inconsistency Factor (*FH*)**	
			Type of Road	
			With paved shoulders	**With Non-paved shoulders**
O	≤ 5 km/h	> - 2 ms $^{-2}$	≤ 2.5	≤ 1.5
A			≤ 3.0	≤ 2.0
B	> 5 km/h		≤ 4.0	≤ 3.0
C			≤ 8.0	≤ 6.0
D		≤ - 2 ms $^{-2}$	> 8.0	> 6.0

* For classes 'O' to 'C', all three criteria ('Speed reduction', 'Deceleration' and '*FH*') must be fulfilled; For class 'D', 'Speed reduction' and only one other criterion ('Deceleration' or '*FH*') have to be satisfied.

Calculation of unimpeded speed profiles in PERVEL is made considering horizontal geometric characteristics only, which hinders the direct application of the method on roads in mountainous areas, with steep grades may exist in considerable amount of road length. This disadvantage dictated the interest in testing the use of IHSDM in the safety assessment of the analysed stretch of IP4.

IP4 CHARACTERISTICS AND SAFETY INTERVENTIONS AND DEVELOPMENTS

Geometric design characteristics

The IP4 road is located in the northern part of Portugal and was the main northern link between the inland populations and the coastal cities until the end of 2005. The studied stretch of IP4 is part of the connection between two major Portuguese cities. From the beginning to km 58.8, the route is a motorway; the studied stretch, from km 58.8 to km 101.9, is a single carriageway road. Due to its location in a mountainous area, the studied stretch has a set of particular design characteristics that seriously affect its safety levels.

The analysed stretch of IP4 is a two lane single carriageway road, with an additional lane for slow vehicles in almost all its ascending gradients. The generic cross section is formed by a 3.5 m lane in each direction, an additional 3.0 m lane in alternate directions for slow vehicles, and paved shoulders with 2.5 m (one lane direction) or 0.5 m (dual lane direction).

FIGURE 1 IP4 - section with climbing lane.

The horizontal layout (114 curves and 110 tangents) has also some peculiar attributes. Horizontal curves account for 69% of the stretch's length, and a considerable number of those have small radius. Around 78% of the horizontal curve radii are smaller than 420 m and 40% smaller than 240 m. These values are specified as the Minimum Absolute Radius for 100 km/h (420 m) and 80 km/h (240 m) design speeds in the Portuguese Road Design Standards (*18*). Furthermore, the majority of the curve and tangent elements are short, making the horizontal layout dangerously sinuous. All horizontal curves have spiral curve transitions.

Regarding the IP4 longitudinal profile, some aspects deserve to be pointed out, as well: 65% of the road length is in gradient steeper than 5%; and a particular section of 11.5 km has 95% of its length with a continuous gradient higher than 6%. Additionally, the majority of the vertical curves have radius smaller than the minimum stipulated by the Portuguese road design standards.

The studied stretch has flexible pavement in all its length. In 2004, when the pavement was 5 years old, a set of road surface characteristics measurements were carried out at the IP4 studied stretch. An average pavement texture depth of 0.72 mm was then obtained with sand patch tests, and skid resistance between 41 and 51 BPN were obtained with the British pendulum test. In the beginning of 2005, a new wearing course was laid out and delineators were installed at the centre line (Figure 1), which had a considerable contribution in improving the road safety levels.

FÎGURE 2 IP4 - section with climbing lane suppressed.

Traffic flow and speed

Traffic data for the studied IP4 stretch was collected from results of the road network traffic census and from traffic counts used for pavement design purposes. The Average Annual Daily Traffic (AADT) at km 86.6 was 11300 vehicles in 2005; near km 100.0, it was 17000 vehicles. Heavy goods vehicles (HGV) accounted for a considerable percentage of traffic: the yearly average was 8.8%. From August to December this ratio was lower, due to a higher number of cars travelling for holidays. Also, mention is made to the fact that the HGV percentage varied considerably during the week: 10.5% during business days and 4.5% on week ends (*19*).

The studied road stretch is an interurban road with a general speed limit of 90 km/h for cars; since the beginning of 2005, 80 km/h local speed limit signs were installed at selected horizontal curves, due to safety reasons. In this study, automatic speed measurements were carried out in 6 different locations, between October 2005 and April 2006. At each location speed was measured in a horizontal curve and in the contiguous tangent. Supplemental measurements were carried out at the beginning, mid point and end of a typical stretch with additional climbing lane.

On curves, the average speed of cars varied between 52 km/h and 73 km/h; for heavy goods vehicles, average speeds were slightly lower (51 km/h to 71 km/h). The 85th percentile speed fluctuated between 70 km/h and 90 km/h for cars, and between 68 km/h and 86 km/h for HGV. Measured standard deviation of the speed distributions were high, ranging from 13 km/h to 21 km/h (coefficient of variation around 0.27). On tangents the average speeds of cars varied between 53 km/h and 79 km/h, the values being slightly higher than on curves. For HGV, average speeds ranged from 52 km/h to 71 km/h. The 85th percentile speed of measured speeds had a minimum of 75 km/h and a maximum of 96 km/h for cars; for HGV, values ranged from 69 km/h to 84 km/h for heavy vehicles. The standard deviations and the corresponding coefficients of variation measured at tangents were similar to the ones measured at curves. Overall, compliance with the maximum speed limit was high on curves: on average, only 7% of the measured speeds were higher than the speed limit. However, in some curves non-compliance percentages were much higher, such as the 25% measured at 78.6 km.

Regarding the sections with the additional climbing lane, measured mean speeds on the right lane were similar to values on single lane sections. However, on the left lane, speeds were significantly higher. The 85th percentile for car speeds was 92 km/h in daytime and 96 km/h at night. Furthermore, one out of four cars exceeded the general speed limit. As expected, on both lanes the maximum speed was measured away from the beginning and the end sections of the climbing lane.

Accident characteristics

Data on registered injury accidents for the period 2000 to 2007 was used in the safety analysis of the investigated stretch of IP4. In this period, a total of 587 injury accidents, 73 fatalities and 121 serious injuries were registered in this stretch of road; injury accidents accounted for almost 40% of all registered accidents.

In Portugal the whole IP4 road was notorious for its bad safety performance, until the end of 2004; this was especially due to the analysed road stretch (15% of the total road length), where 67% of all IP4 accidents occurred. The majority of accidents (72%) occurred at horizontal curves or were related to them. Besides, road design and traffic characteristics, prevailing weather played a role in the IP4 safety performance. Most of the registered accidents (75%) happened when the pavement was wet; and the injury accident rate in rainy months was twice the corresponding figure for the rest of the year.

Between 2000 and 2004 head-on collisions were the most serious accident type, representing 57% of all fatal and serious injury accidents. This can be explained by driver behaviour on the IP4 road, especially in what concerns speed choice, as a significant proportion of head-on collisions was preceded by loss of control. Detailed analysis of all injury accidents that occurred between 2002 and 2005 showed that in several dangerous curves a high percentage of uncontrolled vehicles (40% to 87%) invaded the inside roadside area and crashed there with obstacles and other vehicles. Since 2005 the majority of accidents are ran-off-road accidents (53%).

Safety interventions

Between 2000 and 2004 several safety interventions were implemented on the IP4, namely as regards maintenance of pavement surface characteristics and road markings. In 2000, all intersections were substituted by interchanges, safety equipment and signing were renewed and strict police enforcement was applied for a short period (*20*).

In 2004, climbing lanes were suppressed on some critical stretches (with short sight distances), delineators were installed at the centre line, and a new pavement was constructed, significantly improving skidding resistance on wet conditions (Figure 2). This last intervention was partially successful, as the number of expected accidents was reduced from 312 in the period 2001-2003, to 114 in the period 2005-2007; taking into account the AADT increase between the two time periods, and assuming that the accident risk would be constant, 327 accidents would be expected for the 2005-207 period. Benefits were obtained especially on curves, as the expected number of accidents was reduced from 186 (2001-2003) to 66 (2005-2007), while 194 would be likely, under the above mentioned assumptions.

COMPARATIVE RESULTS OF IHSDM AND PERVEL

In 2005, a complete safety analysis of the IP4 was started, in order to identify remaining deficiencies and plan an integrated set of engineering and enforcement interventions on the infrastructure that might further improve the safety level of the road (*19*).

The PERVEL system was used for evaluating design consistency and, due to the longitudinal profile characteristics of the analysed IP4 stretch, it was also decided to use IHSDM (version 2.08) for the same purpose, attempting to take into account the influence of steep and long grades on speeds and speed profiles. Furthermore, IHSDM was also used to check the expected effect of rearrangements in the cross section layout on the speed differential between cars and trucks along grades, especially at dangerous curves and at curves with restricted sight distance.

Table 2 presents the comparison between the 85th percentile speed measured at selected curves and the calculated speed using both PERVEL and IHSDM. As expected, PERVEL overestimates the traffic speed; the agreement between measured and IHSDM speeds is fair, except at km 86.200, a curve with very low bendiness on the uphill approach. Experience has shown that an extreme speed reduction in poor alignment elements is not consistently well represented by IHSDM (*22*).

TABLE 2 Comparison between calculated and measured speed at selected curves

Station (km)	Length (m)	Radius (m)	Speed (km/h)			Difference in speed (km/h)	
			Measured	PERVEL	IHSDM	PERVEL	IHSDM
59.200	**71**	**-230**	86	92	90	6	4
68.200	**322**	**-230**	70	91	87	21	17
72.900	**281**	**-220**	81	88	86	7	5
79.100	**206**	**-230**	90	91	91	1	1
81.000	**142**	**-230**	80	91	87	11	7
83.900	**119**	**190**	86	93	84	7	-2

Design consistency

Horizontal curves are categorized in five classes, using the PERVEL system (Table 1): class ‘O’ curves do not pose any driver expectancy problem; class ‘A’ curves require small reductions in the unimpeded speed; class ‘B’ and ‘C’ curves require higher speed reductions (at the design stage of new roads they should only be accepted in exceptional cases); class ‘D’ curves are dangerous, as they introduce exceptionally high speed reductions or they force very strong deceleration rates upon the driver. In this case, those unfamiliar with the road will have difficulty to recover from perception errors that may occur in these unusual situations.

Three relevant curve safety indicators are generated with the IHSDM consistency module. One is related to the deceleration rate needed on the approach to the curve, by comparison with the maximum comfortable deceleration rate; the other two are the calculated design consistency measures. One such measure is based on the relation between design speed and operating speed on the curve, and generates four possible outcomes: Condition 1, if V_{85}-$V_{design} \leq 10$ km/h; Condition 2, if 10 km/h < V_{85}-$V_{design} \leq 20$ km/h; Condition 3, if V_{85}-$V_{design} > 20$ km/h; Condition 4, if $V_{design} > V_{85}$. Conditions 1 and 4 do not generate safety concerns. The second design consistency measure is based on the relation between the operating speed on a curve and on the preceding road element. Three outcomes are possible: Condition 1, if $V_{85\ Tangent}$-$V_{85\ Curve} \leq 10$ km/h; Condition 2, if $V_{85\ Tangent}$-$V_{85\ Curve} \leq 20$ km/h; Condition 3, if $V_{85\ Tangent}$-$V_{85\ Curve} > 20$ km/h.

Running PERVEL on the analysed IP4 stretch resulted in seven ‘A’ class curves, eight ‘B’ curves and only one ‘C’ class curve. Several other curves (47) were classified as ‘A’ class curves on one travelling direction only (the other direction being ‘O’ class).

The IHSDM design speed consistency measure was not analysed, as it is dependent on applicable road design standards. As a result of running IHSDM, almost all curves on the analysed IP4 stretch were classified as operating speed “Condition 1” curves; only two curves were classified otherwise, as “Condition 2”. Eight roads elements (three tangents and five curves) presented deceleration rates higher than the maximum comfortable deceleration rate.

IHSDM operating speed “Condition 2” curves corresponded to one PERVEL ‘B’ class and one ‘A’ class (one direction only) curves. No relation was found between the deceleration rate indicator and PERVEL consistency class classification.

A comparison was also made, between the observed safety level on each horizontal curve (periods 2001-2003 and 2005-2007) and the consistency measures obtained using both classification procedures. To this effect, the expected number of accidents on each road element was calculated, using the statistic recommended by Abbess *et al* (*21*) to account for randomness. Then the corresponding expected accident rates were calculated, taking into account the AADT in each element, during the selected periods. Two sets of IP4 road elements were considered in the comparison: the elements with an expected accident rate greater than double but less than four times the average expected accident rate for the whole analysed road stretch; and the road elements with an expected accident rate greater than four times the average expected accident rate for the whole considered road stretch.

Table 3 presents the number of road elements of each consistency class (PERVEL) and each condition (IHSDM) that have less than twice ('-'), between twice and four times ('2×'), and at least four times ('4×') the expected average IP4 accident rate. Both IHSDM Condition 2 curves have at least twice the average accident rate. Six 'A' class and six 'B' class PERVEL curves showed accident rates below double the average for the IP4 stretch; however, with the detailed analysis of accident data it was detected that several accidents related to road curves were located by the police as occurring on tangents, nearby the relevant curves.

TABLE 3 Number of elements per road consistency class and expected average accident rate

Procedure	Consistency Class	Accident rate level					
		2001 - 2003			2005 – 2007		
		4×	2×	-	4×	2×	-
PERVEL	A	1	0	6	0	2	5
	B	2	0	6	0	0	8
	C	0	1	0	0	0	1
	a*	2	4	41	2	3	42
IHSDM	Condition 2	1	1	0	0	0	2
	Deceleration	0	0	8	0	1	7

* 'A' class in one direction only.

Table 4 presents the number of road elements of a given expected accident rate level that belong to a given consistency class (PERVEL) and each condition (IHSDM).

TABLE 4 Number of elements per expected average accident rate and road consistency class

Period	Accident rate level	Consistency Class								
		PERVEL					IHSDM			Tangent
		A	B	C	a*	O	2	Dec	-	
2001 - 2003	2×	-	-	1	47	15	1	-	19	7
	4×	1	2	0	2	14	1	-	18	11
2005 - 2007	2×	2	-	-	3	37	0	1	41	31
	4×	-	-	-	2	9	-	-	11	6

* 'A' class in one direction only.

As mentioned before, the number of accidents registered on curves is smaller than the number of accidents related to horizontal road curves, as several of these accidents are registered by the police as having occurred in adjacent tangent elements.

Road elements with high speed differential between cars and heavy goods vehicle

The operations module of IHSDM was used to detect stretches where great differences between car and HGV desired operating speeds might be expected to occur.

Two sets of low hourly traffic flows were used, to simulate low traffic conditions, in order unimpeded speeds were obtained: 100 vehicles per hour, resulting in the identification of 13 km of road where HGV speed is more than 20 km/h lower than the speed of cars; and 500 vehicles per hour, resulting in the detection of 3.7 km of road where HGV speed is more than 20 km/h lower than the speed of cars.

In the period 2000–2004, the average expected accident rate on normal stretches (0.450 accidents per million vehicle×km) was half the average expected accident rate (0.849 accidents per million vehicle×km) on the stretches detected with the lowest hourly traffic flow. However, in the period 2005–2007 the average expected accident rate on normal stretches (0.189 accidents per million vehicle×km) was (almost 40%) higher than the average expected accident rate (0.132 accidents per million vehicle×km) on the stretches detected with the lowest hourly traffic flow, which is not in accordance with existing references (*17*). The low number of expected accidents during the period 2005–2007, in the 13 km stretch where high speed differentials are expected to occur, may partially explain these results. However, under specific circumstances, such as no passing zones with long visibility distance, HGV may contribute to reduce the desired speed of car drivers.

Comparison between Crash Prediction Module results and expected accidents in the three year period 2005-2007

The crash prediction module (CPM) was used to estimate the safety effects of the suppression of climbing lanes at selected road stretches (which was implemented in 2005). Only the roadway segment accident prediction algorithm was calibrated to the Portuguese accident data, as there are no intersections on the IP4 analysed stretch (only interchanges).

Data on ADT, carriageway and shoulder widths were available for two lane single carriageway roads of the NRN, allowing for a Level 2 calibration process (*22*). As there are no available inventory data on alignment (horizontal curvature and grade) or the terrain characteristics, the percentages of road length in flat, rolling and mountainous terrain were estimated on the basis of the road district. The calculated value for the calibration factor for highway segments (Cr) was 2.299. No changes were made to the default values for shoulder type, driveway density, passing lane, roadside hazard rating and other geometric parameters; however, spiral transition are consistently used on Portuguese road curves. Crash type and severity distributions were calibrated using data (2000-2005) for the NRN (*22*).

The results obtained with the crash prediction module of IHSDM were compared with the expected number of accidents per road element derived from registered accidents during the three year period 2005 to 2007. Some differences were observed, as described in the following paragraphs.

The total number of injury accidents estimated with IHSDM was considerably higher that the observed number of accidents (286 vs. 114). This was more important for curves (156 accidents vs. 36) than for tangents (130 vs. 78). The mentioned 2004 safety intervention may explain these differences, as the resulting layout of the road differs considerably from the layout of other NRN single carriageway roads that were used for CPM calibration. It is expected that a disaggregation of single carriageway roads by category (trunk road, complementary route and regional road) may improve the CPM calibration, even though each calibration procedure will be based on fewer roads.

A comparison was also made between the distribution of expected accident densities (crashes per km) in the period 2005 and 2007 and the densities calculated using IHSDM. Two relevant levels of accident density were selected for the comparison: stretches with accident density greater than four times the average accident density on the analysed IP4 (“4×”); and the stretches with accident density greater than twice but lower than four times the average accident density on the analysed IP4 (“2×”). The results are presented in Figure 4 where the axis marked “Expected relative densities” corresponds to the ratio between the expected accident densities and the average expected accident density, calculated with registered accident data; and the “IHSDM relative densities” axis corresponds to similar ratios, of values calculated with the crash prediction module.

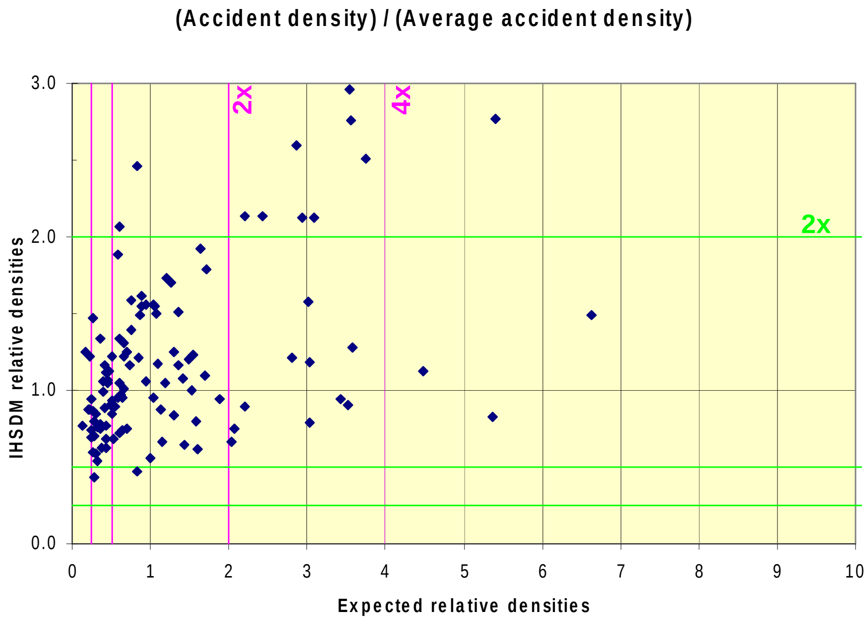

FIGURE 4 Comparison of accident densities on horizontal curves.

It is relevant to note that the distribution of IHSDM accident densities does not contain stretches classified as “4×”. This might be expected, as the models represent only the influence of the most important and enduring systematic accident factors and do not incorporate the influence of several temporary factors. It is also noticeable that almost all IHSDM curves classified as “2×” or above correspond to curves where the expected number of accidents was classified as “2×” or above. Therefore, results from the CPM are useful in the *a priori* detection of dangerous curves, leading to few false positive cases; from Figure 4 it can be concluded that a significant number of curves with high expected number of accidents (‘2x’ or above) was not identified as such with IHSDM (there was a significant number of false negatives).

CONCLUDING REMARKS

Results from the application of the design consistency procedures tested in the analysis of the 43 km IP4 stretch showed that detected inconsistent curves are, indeed, associated with higher accident frequencies than the remaining road elements. This indicates that both procedures are successful in helping designers to detect safety problems related to geometric design consistency, when designing new roads or redesigning existing ones. The results obtained also showed that not all dangerous curves are detected by any of the tested procedures, highlighting the fact that the topic of safety on horizontal curves is not restricted to the issue of geometric consistency.

Consideration of both horizontal plan and longitudinal profile characteristics is advisable when evaluating the design consistency of roads in mountainous terrain.

Application of the IHSDM crash prediction module resulted in a significant overestimation of the expected accident frequencies on IP4 road elements, in spite of considerable effort spent on calibrating the algorithms to Portuguese accident characteristics. It remains an open issue if this disadvantage may be mitigated by using a more complete evaluation of each road stretches’ terrain, by resorting to alignment data or simply by developing specific calibration factors for each road class. It is expected to address this issue in future work, as soon as more complete inventory data on existing National Road Network roads became available. It is believed that the integration of accident prediction models fitted to the Portuguese context would enhance the usefulness of this module.

Results obtained with the application of the CPM demonstrated its effectiveness in the detection of dangerous road curves, stressing the merits of its use at the design stage. Furthermore, by setting a transparent standardized way for estimating expected safety levels, the crash prediction module meets the need for a tool to support decision making on alternative design details for a road.

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