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APPLICATION OF THE IHSDM FOR ANALYSIS OF ROAD DESIGN CONSISTENCY AND ASSESSMENT OF THE NUMBER AND TYPE OF TRAFFIC ACCIDENTS: A CASE STUDY OF THE CROATIAN STATE ROAD DC1

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Abstract

Generally, statistical data show that more than 50% of fatal traffic accidents occur on rural two-lane roads, with over half being related to horizontal curves. Accident locations indicate that road alignment consistency has a significant impact on accident occurrence. Many crash prediction models and road design consistency models have been developed, mostly based on operating speed and road geometric characteristics. In this paper, the Interactive Highway Safety Design Model (IHSDM) was used to analyse the consistency of road horizontal and vertical elements, as well as to predict the number and type of crashes on a section of the state road DC1 from Vrlika to Hrvace, covering a length of approximately 24 km. Two modules within the software were utilized: the module for predicting the number and types of accidents (Crash Prediction Module - CPM) and the consistency of the road alignment module (Design Consistency Module - DCM). In this regard, two types of road alignment consistency analyses were conducted: one according to the Croatian road design guidelines and another using the IHSDM tool. Furthermore, a comparison between the estimated and actual number of accidents was performed. The comparison showed that the number of accidents predicted by the IHSDM software does not deviate significantly from the actual number of traffic accidents on the analysed section. Based on the results of the conducted analyses, locations along the road section with reduced safety were identified, and infrastructure measures were proposed to improve traffic safety, specifically in terms of reducing the number of accidents.

Keywords: Crash Prediction Module (CPM), Design Consistency Module (DCM), Interactive Highway Safety Design Model (IHSDM), road design consistency, traffic accidents

1 Introduction

Traffic accidents represent a significant world health and safety problem, ranking 12th among the most common causes of death worldwide, with approximately 1.19 million deaths globally in 2021 [1]. The average annual number of traffic accidents on the roads of the Republic of Croatia for the period from 2010 to 2020 was 33, 554 [2]. Generally, a significant portion of fatalities (more than 50%) result from accidents on rural two-lane roads, and at least half of which are associated with horizontal curves [3]. The occurrence of traffic accidents is not solely due to one factor but can be attributed to a combination of several. However, a higher number of traffic accidents at specific locations is a direct indicator of inadequate road characteristics. One of the most common causes of traffic accidents in horizontal curves is the lack of consistency, meaning the mismatch of the alignment elements with drivers' expectations. Alignment elements should be harmonized to enable safe, comfortable, and economical driving, without situations that require significant and abrupt speed changes.

Therefore, the concept of alignment consistency is an important procedure in the road design process. Various measures exist in the literature for ensuring alignment consistency, most of which are based on operating speed. Operating speed (V_{85}) is usually determined as the 85th percentile speed and refers to specific alignment elements (horizontal curve or tangent). Certain measures for ensuring alignment consistency are included in road design guidelines. Models for predicting traffic accidents are a useful tool for road safety improvement. One of the most commonly used models is the Crash Prediction Module (CPM) within the Interactive Highway Safety Design Model (IHSDM) software, developed by the Federal Highway Administration (FHWA) [4]. In Croatia, models for predicting traffic accidents have not been developed so far.

In this study, an analysis of the alignment consistency was conducted for a 24 km section of the state road DC1 from Vrlika to Hrvace. First, the consistency of alignment elements was analysed using the Design Consistency Module (DCM) within the IHSDM software, and a review of measures for road alignment consistency from the Croatian road design guidelines [5] was made. Second, the IHSDM Crash Prediction Module (CPM) was applied to predict the number of traffic accidents based on the geometric characteristics of the alignment, traffic flow characteristics, and historical data on traffic accidents from that section.

2 Interactive Highway Safety Design Model (IHSDM)

Interactive Highway Safety Design Model (IHSDM) is a tool used to assess the safety and operational performances of roads, and it can be utilized for both planned and existing roads. Specifically, it enables the examination of safety for planned roads and allows for certain improvements to be made during the design process. Moreover, it is possible to check for potential countermeasures for existing roads in order to reduce the likelihood or severity of traffic accidents and enhance overall road safety. IHSDM consists of five modules: Crash Prediction (CPM), Design Consistency (DCM), Policy Review (PRM), Traffic Analysis (TAM), and Driver/Vehicle (DVM). In this study, the CPM and DCM will be used, so the basic characteristics of these modules are presented below.

2.1 Crash Prediction Module (CPM)

This module is used to assess the frequency and severity of traffic accidents on a particular road, based on its geometric and traffic characteristics, providing the opportunity to compare different alternative solutions. The CPM is based on methods defined in the Highway Safety Manual (HSM) [6] and can be used for various elements of the transportation system. The crash prediction algorithm consists of baseline models or safety performance functions (SPFs), crash modification factors (CMFs), and calibration factors. The equations for predicting the number of crashes for road segments are [6]:

$$N_{rs} = C_r \cdot N_{spf\text{-}rs} \cdot (CMF_{1r} \cdot \ldots \cdot CMF_{nr}) \tag{1}$$

$$N_{spf\text{-}rs} = AADT \cdot L \cdot 365 \cdot 10^{-6} \cdot e^{-0.312} \tag{2}$$

where N_{rs} = predicted number of crashes for roadway segment per year, C_r = calibration factor for roadway segments, $N_{spf\text{-}rs}$ = predicted number of roadway segment crashes per year for baseline conditions, CMF_{nr} = crash modification factors for roadway segments, AADT = average annual daily traffic volume on roadway segment (veh/day), and L = length of roadway segment (m). The base conditions involve 3.6 m lane width, 1.8 m of shoulder width, roadside hazard rating of 3, driveway density of 5, no horizontal curvature, no grade, no centreline rumble strip, no auxiliary lane, no lighting, and no speed enforcement.

The base model is further adjusted by each CMF, considering particular road design and traffic control features. Additionally, this module has the capability to combine model estimates with locally recorded crash history data using an Empirical Bayes procedure. Roadside hazard rating is a system for evaluating roadside safety conditions (clear zone in conjunction with the roadside slope, roadside surface roughness, recoverability of roadside, and some barriers or trees beyond the clear zone). It can be described with a scale factors from 1 to 7, where higher values represent greater crash risk frequency and/or severity. Driveway density represents the number of driveways per kilometre on both sides of the driveway combined [6].

2.2 Design Consistency Module (DCM)

The DCM focuses on assessing operating speed along a roadway using a speed-profile model. This module is based on Lamm's safety criteria I and II [3] and incorporates the following two measures:

A. The difference between estimated operating speed (V_{85}) and design speed (V_d), and
B. The expected reduction in V_{85} from an approach tangent to horizontal curve.

The speed-profile model employed in the DCM was calibrated using data collected from various two-lane rural roads across the USA. Considering that speeding is one of the most common causes of traffic accidents, this module represents a simple and useful tool for identifying potentially hazardous locations along the route. In addition to the basic geometric road characteristics, this module includes input data such as the speed limit posted along the roadway, design speed, desired speed, and roadside hazard rating. The desired speed refers to the 85th percentile speed selected by drivers on long tangents, not constrained by the vertical or horizontal alignment. Based on the results of several studies and recommendations from the IHSDM Manual [4], the value of 97 km/h was used in this paper.

3 Analysis

Two types of analyses were conducted in this study: analysis of road design consistency using IHSDM - DCM and prediction of the frequency and severity of traffic accidents with the IHSDM - CPM.

3.1 Characteristics of the analysed road section

The analysis was conducted on approximately 24 km long section of the state road DC 1, from Hrvace to Vrlika. It is a two-lane rural road, with a constant lane width of 3.5 m, consisting of 103 horizontal curves (80 m < R < 1500 m) and 97 tangents (with lengths up to 600 m). The analysed road section was designed many years ago, so the geometric elements were defined from the road survey, which was made in 2006 by Croatian Roads Ltd. In most cases, horizontal curves were constructed without a spiral transition curve between the tangent and the circular curve or with a short one (20 or 30 m in length). The grades range from 0 to 6%, and the design speed is 60 km/h. The posted speed limit for the majority of the segment is 60 km/h, with three shorter sections having a limit of 80 km/h. It is a road section with relatively low traffic volume and no major intersections.

3.2 CPM analysis

Apart from basic geometric characteristics, the following data were also considered for the CPM analysis: AADT, V_d, driveway density, roadside hazard rating, and locally recorded crash history data. Historical crash data from the analyzed section for a 5-year period (2016 – 2020) were obtained from the local police station (Table 1). According to the consequences, traffic accidents were divided into fatal and injury (FI) crashes and property damage only (PDM) crashes. Furthermore, traffic accidents were categorized according to different types, whereby single-vehicle accidents and accidents involving multiple vehicles were grouped separately. Out of a total of 154 traffic accidents in the specified period, 3 were fatal accidents: one run-off-road and two head-on crashes. The cause of the run-off-road and one head-on crash was inappropriate speed, while the cause of the other head-on crash was crossing onto the opposing lane.

In the period from 2016 to 2020, the AADT was 1473 veh/day [7], and the latest data shows 1553 veh/day for the year 2022. Considering the roadside hazard rating, the analyzed road section can be classified as factor 6 out of 7.

Historical crash data (from 2016 to 2020) and the analysis results are presented in Table 1. In order to evaluate the capability of CPM to produce reasonably reliable crash predictions in the Croatian context, two types of analyses were made: "Analysis I" for the future 5-year prediction period not considering historical crash data and "Analysis II" for the future 5-year prediction considering crash history. Since the exact locations of traffic accidents are not known, the effect of historical crash data was considered for the whole project, as a list of individual crashes that occurred during a 5-year period.

Table 1 Historical crash data (2016 - 2020) and the CPM analysis results

Crash type	2016 - 2020		ANALISYS I (2025 – 2030)		ANALISYS II (2025 – 2030)	
	Crashes [%]	Crashes [%]	Crashes [%]	Crashes [%]	Crashes [%]	Crashes [%]
Fatal and injury crashes						
Collision with animal			1.57	1.2	2.16	1.2
Collision with bicycle	1	0.6	0.17	0.1	0.23	0.1
Other single-vehicle collision			0.29	0.2	0.40	0.2
Overturned			1.53	1.2	2.10	1.2
Collision with pedestrian	4	2.6	0.29	0.2	0.40	0.2
Run-of-road	28	18.2	22.55	17.5	30.96	17.5
Total single-vehicle crashes	33	21.4	26.4	20.5	36.25	20.5
Angle collision			4.18	3.2	5.74	3.2
Head-on collision	22	14.3	1.41	1.1	1.93	1.1
Sideswipe			1.57	1.2	2.16	1.2
Rear-end collision	5		6.83	5.3	9.37	5.3
Other multiple-vehicle collision			1.08	0.8	1.48	0.8
Total multiple-vehicle crashes	27	17.5	15.07	11.7	20.68	11.7
Property damage only crashes						
Collision with animal	16	10.4	16.1	12.5	22.11	12.5
Collision with bicycle			0.09	0.1	0.12	0.1

Table 1 Historical crash data (2016 - 2020) and the CPM analysis results

The results in Table 1 lead to the following conclusions:

Crash type	2016 - 2020		ANALISYS I (2025 – 2030)		ANALISYS II (2025 – 2030)	
	Crashes [%]	Crashes [%]	Crashes [%]	Crashes [%]	Crashes [%]	Crashes [%]
Other single-vehicle collision	4	2.6	2.54	2.0	3.48	2.0
Overturned			1.31	1.0	1.80	1.0
Collision with pedestrian			0.09	0.1	0.12	0.1
Run-of-road	21	13.6	44.2	34.3	60.68	34.3
Total single-vehicle crashes	41	26.6	64.33	49.9	88.31	49.9
Angle collision	42	27.3	6.3	4.9	8.65	4.9
Head-on collision			0.26	0.2	0.36	0.2
Sideswipe			3.33	2.6	4.57	2.6
Rear-end collision	11	7.1	10.68	8.3	14.66	8.3
Total multiple-vehicle crashes	53	34.4	23.2	18.0	31.84	18.0
Total crashes	154	100.0	129.0	100.0	177.08	100.0
Crash rate (crashes/km/yr)	1.0267		0.8593		1.1797	
FI crash rate (crashes/km/yr)	0.4000		0.2758		0.4554	
PDO crash rate (crashes/km/yr)	0.6267		0.5835		0.9612	

- “Analysis II” predicted a 15% higher number of accidents than the actual (177 vs 154), while “Analysis I” predicted a 16% lower number of accidents compared to the actual (129 vs 154).
- “Analysis II” predicted 10% more FI single-vehicle accidents than the actual, 23% fewer FI multiple-vehicle crashes than real, more than double PDO single-vehicle accidents than real, and 40% fewer PDO accidents compared to the actual number. Namely, CPM was evaluated and calibrated based on data from the USA and does not fully correspond to the distribution in the Croatian area. This could be improved with more detailed records of traffic accidents, with accurate locations where the accidents occurred.
- -Similar to the total number of accidents, “Analysis II” resulted in higher values than the actual crash rate (1.1797 vs 1.0267), while “Analysis I” resulted in lower values compared to the actual (0.8593 vs 1.0267).
- -When comparing the crash rate values for FI crashes, “Analysis I” resulted in a 31% lower, and “Analysis II” 14% higher value compared to the actual crash rate. For PDO crashes, “Analysis I” resulted in a 7% lower, and “Analysis II” 53% higher value compared to the actual crash rate.

The position of the road geometric alignment elements is determined by the existing terrain, and significant changes to the route require greater investments, thus their economic viability should be further examined. Therefore, this paper will only analyze the impact of improvements in terms of certain infrastructure measures that require smaller investments. Improvements can be achieved in the following ways: increasing the clear roadside recovery distance; reducing roadside slope and roadside surface roughness; introducing lighting, automated speed enforcement, and centerline rumble strips. Additional analysis was conducted regarding improvements in roadside safety conditions, considering a lower road-side hazard rating scale factor, the presence of lighting, automated speed enforcement, and centerline rumble strips. A roadside hazard rating factor of 3 was considered, typical for baseline conditions. It implies a clear zone of about 3 m, a sideslope of about 1:4, and marginally recoverable conditions in terms of roadside surface roughness. For comparison, factor 6, defined for existing conditions, implies a clear zone less than or equal to 1.5 m, a sideslope of about 1:2, and non-recoverable roadside surface roughness conditions. The additional analysis resulted in a total of 166.23 accidents, of which 53.36 were FI crashes and 112.87 were PDO crashes. The total crash rate is 1.1082, the FI crash rate is 0.3557, and the PDO crash rate is 0.7525. Compared to the results of "Analysis II", this represents a reduction in the total number of accidents and the total crash rate by 6%.

3.3 Road design consistency analysis

The Croatian road design guidelines [5] include road alignment consistency measures based on Lamm's safety criteria [3], also included in IHSDM. However, in the Croatian guidelines, a project speed is used instead of operating speed. It is a theoretical value, determined as a function of the curve radius or the steepest grade. Furthermore, in the Croatian guidelines the following road design consistency measures are defined: the difference between the project and design speed must not exceed 20 km/h, the difference between the minimum and maximum values of the project speed within the same section must not exceed 15 km/h, the diagram of the relationship between the radii of successive curves, and the ratio of the tangent length to the adjacent curve radius. The analysed road section was designed many years ago, according to older road design guidelines, and therefore is not in accordance with the current Croatian road design guidelines [5]. For example, inconsistencies in the adjacent curve radii were observed in 84% of the curves along the analysed section.
The road alignment consistency analysis was conducted using the DCM within the IHSDM program. The Design Consistency Module resulted in speed profiles for travel in both directions, and Figure 1 shows the speed profile for the direction from Vrlika to Hrvace.

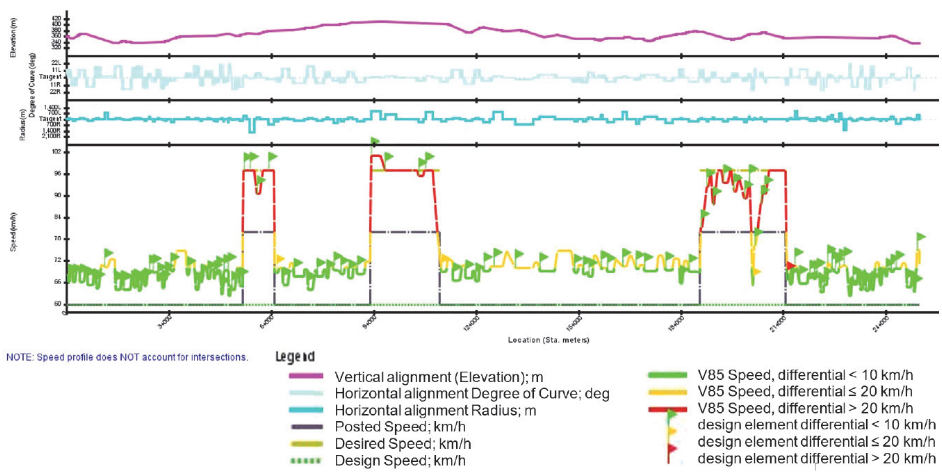

Figure 1 The Speed-profile along the horizontal and vertical alignment of the analysed road section in the direction from Vrlika to Hrvace

For easier visual inspection, the colour-coded results of two design consistency checks (measures "A" and "B" from the section 2.2) are presented in the graphical output: green – condition 1 ($\Delta V \leq 10$ km/h), yellow – condition 2 (10 km/h $< \Delta V \leq$ 20 km/h), and red – condition 3 ($\Delta V >$ 20 km/h). Colour of the speed profile line indicates the deviation of operating from design speed, while the colour of the flag on the speed profile set at the beginning of each horizontal curve indicates the level of operating speed reduction from approach tangent to that curve. The results clearly indicate locations with reduced safety. Namely, different design consistency levels are based on extensive speed and accident databases from various countries. Researches indicate that average crash rates for curves requiring speed reductions greater than 20 km/h were six times the average crash rates for curves requiring less than 10 km/h. The average crash rates for curves with 10-20 km/h speed reduction were three times greater than for curves with less than 10 km/h speed reduction [4].
Considering the comparison between design speed and operating speed (measure "A" from the section 2.2) from the Figure 1, three locations with condition 3 can be identified. These segments consist of flatter horizontal elements (with a posted speed of 80 km/h) located between road sections with smaller radius curves (and lower posted speeds of 60 km/h). The operating speed estimated and predicted by DCM is influenced by the posted speed limit.
Regarding the measure "B", one red flag was observed, indicating a speed reduction from the previous element greater than 20 km/h (condition 3). This location refers to a curve with a radius of 240 m preceded by a 572 m long tangent. Such combinations should be avoided in design because they require significant and sudden changes in speed, which very often have negative consequences. In such situations, there is a loss of control or vehicle stability as a result of exceeding the optimum values of side friction due to inappropriate or excessive speed. Therefore, such situations can result in run-off-road or head-on crashes, which are one of the most common fatal accidents.

4 Conclusions

The IHSDM program was applied to analyse the road design consistency and assess the number and type of traffic accidents along a 24 km section of the state road DC 1. The DCM analysis identified potentially hazardous locations on the route, revealing speed inconsistencies. Furthermore, the CPM analysis which utilized crash history data, yielded superior results compared to the analysis conducted without considering crash history data. The comparison demonstrated that the number of accidents predicted by the IHSDM software aligns closely with the actual number of traffic accidents on the analysed section. Therefore, it can be concluded that the IHSDM program can be utilized for relative comparison of multiple variant solutions and for testing certain improvements. These improvements can target geometric alignment elements and infrastructure measures, ultimately aimed at enhancing safety and reducing the number of accidents.

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