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Safety Impact Prediction of Redesigning National Roads Crossing Residential Areas: An Italian Case Study

Maurizio Crispino, Kevin Camozzi, Misagh Ketabdari, Arianna Antoniazzi * and Emanuele Toraldo

Department of Civil and Environmental Engineering, Politecnico di Milano, 20133 Milano, Italy; maurizio.crispino@polimi.it (M.C.); kevin.camozzi@mail.polimi.it (K.C.); misagh.ketabdari@polimi.it (M.K.); emanuele.toraldo@polimi.it (E.T.)

* Correspondence: arianna.antoniazzi@polimi.it

Abstract: The purpose of this study is to determine the safety effectiveness of an intervention on an existing road by using predictive methods. Predictive methods allow the benefit of the intervention to be quantified in terms of crash reduction. Currently, the most widely used model is reported in the Highway Safety Manual, developed in the US. The HSM model is adapted to the Italian context through a calibration procedure. The model is then applied to two future scenarios: in the absence and presence of intervention. The redesign intervention consists of rehabilitating some road sections and constructing five tunnel bypasses to avoid crossing residential areas. The comparison between the 'with' and 'without' scenario estimated an overall reduction in the number of accidents of around 45%. The variant scenario is based on reasonable assumptions that allowed the determination of the proportion of traffic that will be diverted to the variant. In addition, several alternative future scenarios are considered to assess a possible different trend in assumed traffic distribution. Moreover, a possible overall increase or reduction in total traffic affecting the road is taken into account. The results showed that the intervention provided significant benefits even with increased traffic, proving the resilience of the intervention.

Keywords: road safety; road crashes; predictive methods; crash modification factors; road bypass; redesign effectiveness; road rehabilitation; crash reduction

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1. Introduction

The European Union has set a target of 50% reduction in the number of road fatalities and serious injuries by 2030 and complete elimination by 2050; thus, specific strategies have been proposed [1]. However, apart from the COVID-19 pandemic period, the actual reduction trend shows a low possibility of meeting these targets [2]. The accident trend in Italy is also not expected to meet the targets [3].

To date, a widely adopted approach to improve road safety is the Safe System approach, which aims to eliminate any latent risk in the infrastructure to make it inherently safe for users [4–7]. To this end, predictive safety methods could offer significant benefits. In fact, predictive models enable one to determine the safety performance level of specific infrastructure according to its geometric–functional characteristics. Consequently, maintenance planning based on the application of these models supports road managers in making decisions aimed at maximizing socio-economic benefits in terms of lives saved [8]. This approach can be considered as a complementary method to be used in parallel with other decision-making tools (e.g., economic evaluation, sustainability assessment, and social impact analysis). Indeed, the possible outcome of rehabilitation/maintenance interventions in terms of expected crashes could be assessed before implementation. In addition, predictive models can be applied to determine the variability of intervention effectiveness as a function of boundary conditions, such as traffic.

In general, to identify the most appropriate intervention solution among various alternatives, a confrontation between their implementation cost and the deriving safety

benefit is required. For this purpose, one of the most diffused approaches is the cost–benefit analysis. However, the present study is mainly focused on a particular redesign intervention; thus, the safety impact is solely quantified in terms of crash reduction rate.

In the following, as the first step, data regarding traffic, accidents, and road characteristics are collected (in Section 4) in order to apply predictive models. Then, a specific procedure should be followed, as explained in Section 5, to simulate future scenarios, which enable to evaluate the impact of the redesign intervention.

2. Literature Review

Predictive methods for road safety were first introduced in the Highway Safety Manual (HSM), published in 2010 (and subsequently revised in 2012) by the American Association of State Highway and Transportation Officials (AASHTO) [9]. The HSM predictive model serves as the primary reference in this field and is used to develop this study. It is worth noting that a further revision of the HSM model is currently underway, with a preliminary document already published and referenced below [10]. The road infrastructure under study comprises a section of an Italian national road with a single carriageway and one lane in each direction. Therefore, Chapter 10 of Part C of the HSM [9] was considered, as it deals with rural two-lane two-way roads.

Since road accidents are affected by the phenomenon of regression to the mean, which causes random fluctuations of crashes around the mean value, accident statistics must be carefully considered. In fact, a sufficiently large time interval must be taken into account to mitigate the effects of accident variability. This step is crucial, especially when selecting the most critical locations on the road network for maintenance. If the aim is to compare two situations with and without intervention, it is essential that the situation without intervention is realistic and representative of the safety conditions at the site. To assess safety conditions, different safety performance indicators have been developed. The Italian authorities proposed some indicators (e.g., crash rate, crash frequency, and crash number), ranked according to their priority, but still referring to observed crashes [11]. However, to address the issue of regression to the mean, predictive models need to be used to provide a more reliable assessment of the actual safety of an infrastructure. Specifically, the reliability of predictive models depends on estimation accuracy, derived from the model calibration procedure. The use of these models then allows one to perform Empirical Bayesian analysis (EB analysis), which is an effective tool for determining the most likely number of crashes to be expected on a road.

However, adopting the HSM predictive model to the Italian context involves a process of adaptation based on the calibration phase. Other studies conducted in Italy have involved the application of an HSM predictive model [12–16] or alternative models similar to HSM [17]. In fact, the transferability of HSM to a different context has been assessed by many national and international studies [18–29].

The properly calibrated model can then be used to run simulations of different alternative scenarios. These models have been used in the past to evaluate the effectiveness of specific maintenance measures involving, for example, pavements [30–32], lighting [33,34], left-turn maneuver signal [35], shoulder paving [36], medians [37], rumble strips [38], or generally cost-effective interventions [39]. However, the literature studies often deal with the evaluation of each intervention separately, without considering possible solutions affecting different infrastructure characteristics. According to the literature, some research is devoted to the correlation between maintenance and safety status of the roads [40–42], but a few are taking into account the road boundary conditions, which can be found in an Italian context [43].

3. Research Objectives

For this study, the construction of a variant to the existing route makes it possible to redistribute traffic and provides users with an infrastructure that is safer and complies with national technical regulations. In particular, the variant design includes adequate lane

and shoulder widths, no direct accesses, and the presence of protected edges. In addition, the rehabilitation of the existing route involves the revision of the radii of curvature, the reorganization of the accesses and a general improvement in the safety conditions of the infrastructure. Predictive methods need to be used to assess the overall impact of these interventions before implementation.

The aim of this study is first to adapt the HSM predictive model to the Italian national road under investigation and then to carry out simulations on the effect of the planned redesign interventions. This allows the potential safety impact to be quantified in terms of crash reduction.

4. Data Collection

To assess the possible impact of redesign interventions on rural single carriageway roads, a case study of an Italian national road is considered. The first step involves collecting data for the existing road under investigation. In particular, traffic data, accident data and geometric–functional characteristics of the existing road are required. Furthermore, specific details of the planned redesign interventions are needed.

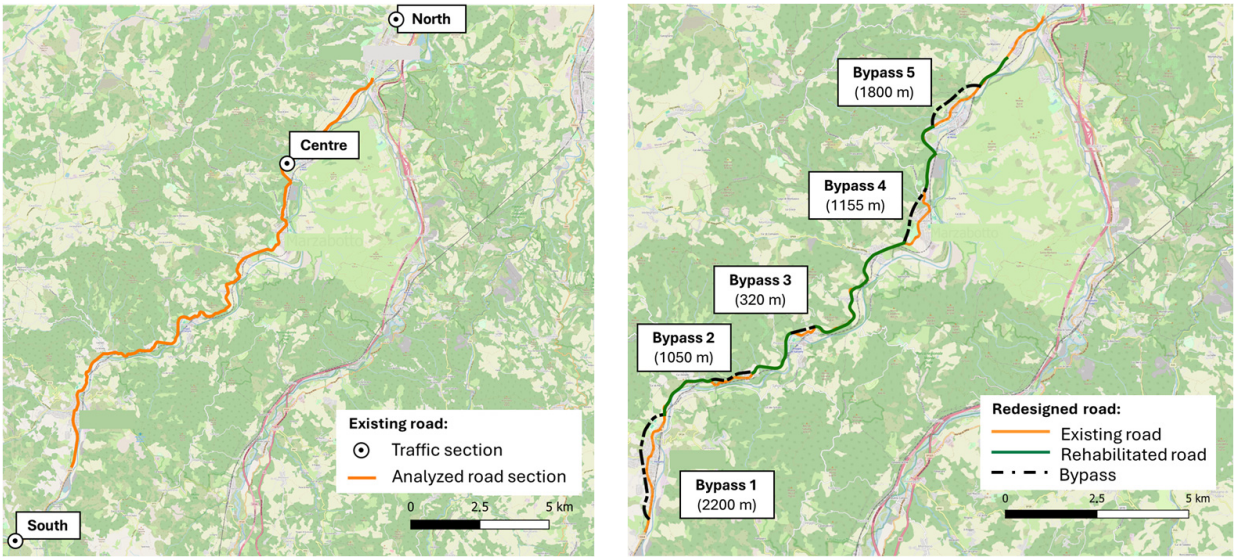
All time-varying data, such as traffic, must be evaluated for each year of the total time interval considered. Given that the road section under consideration spans approximately 20 km, it is necessary to consider a long time period of 9 years (from 2014 to 2022) to gather a sufficiently large database.

4.1. Traffic Data and Accident Data

The traffic volume on the analyzed existing road sections during the reference period (9 years from 2014 to 2022) was extracted from the regional web portal [44]. In particular, the traffic is known at three survey stations located close to the road section under study. Historical accident data were collected for the analyzed road section for the same time interval (2014–2022). Crash data at the selected sites were retrieved both from the web-page of the municipality [45] and the portal of the National Statistical Institute (ISTAT) [46]. The Annual Average Daily Traffic (AADT) values and the overall number of crashes that occurred during the considered time interval on the analyzed road are synthesized in Table 1. The traffic values refer to both directions of travel as these are single carriageway roads. Consequently, the number of observed accidents associated with each road section includes accidents occurred in both directions. The location of the available traffic sections on the map is illustrated in Figure 1a.

Table 1. Summary statistics of traffic data (AADT) and crash data.

Annual Average Daily Traffic—AADT [vehicles/day]				**Observed Crashes with Injuries and Fatalities (N_{obs})**			
Year	**Traffic Section**			**Year**	**Crashes**	**Injuries**	**Fatalities**
	North	**Centre**	**South**				
2014	13,665	12,416	7883	**2014**	19	27	0
2015	13,468	12,602	8136	**2015**	22	42	0
2016	13,448	12,649	8249	**2016**	24	35	0
2017	11,866	12,682	8377	**2017**	23	40	0
2018	10,850	13,331	8499	**2018**	32	53	3
2019	10,861	12,393	8401	**2019**	20	38	1
2020	8873	9464	7030	**2020**	28	47	0
2021	10,882	11,033	8052	**2021**	21	47	0
2022	12,370	11,783	8226	**2022**	32	48	1
Average (*Standard deviation*)	12,010 (*1637*)	12,068 (*1097*)	8073 (*422*)	**Total** (*9 years*)	221	377	5
Minimum	8873	9464	7030	**Average** (*1 year*)	25	42	1
Maximum	13,817	13,331	8499				



(**a**) (**b**)

Figure 1. Location of analyzed road: (**a**) existing road and traffic sections; (**b**) redesigned road.

4.2. Geometric–Functional Road Characteristics

Data on the geometric and functional characteristics of the 20 km section of existing road were collected. In particular, the examined road has one carriageway with one lane per direction. The procedure for recording data on existing road characteristics is based on the adoption of specific software to collect geo-referenced information on the geometric-functional characteristics of each element. In the absence of a complete database of infrastructure characteristics, these were determined and entered into the software pseudo-manually.

As a first step, the road was divided into intersections and segments, which were defined between the center of successive intersections. In addition, each segment was subdivided into smaller homogeneous sections. Segments were classified into curves and straight lines, while intersections were classified according to the regulation method and the number of legs. Figure 1a represents the location of the analyzed section of the existing road.

Road redesign was planned to improve traffic flow and safety on the road concerned. In particular, the construction of five tunnel bypasses and the rehabilitation of the existing route was planned. The five bypasses had lengths, respectively of 2200 m, 1050 m, 320 m, 1155 m, and 1800 m and were developed in the five sections shown in Figure 1b. The construction of these bypasses will create alternative paths to the existing route and divert traffic flow away from residential areas. This solution will reduce vehicle conflicts associated with the numerous intersections and driveways on the existing route. In fact, there are no crossings or junctions along the entire length of the tunnel bypasses.

At the same time, the rehabilitation of the existing route improves safety by reducing planimetric curvature and reorganizing the road platform and accesses, thereby enhancing the intrinsic safety characteristics of the road.

The necessary information on geometric–functional road characteristics is collected both for the existing road path and for the redesigned layout. The gathered data are divided between segments and intersections, as summarized in Table 2. These data are needed for the subsequent calculation of the Crash Modification Factors (CMFs), which will be discussed in Section 5.4.

Table 2. Summary statistics of the geometric data (segments and intersections) for the existing road and redesigned road.

		Existing Road		Redesigned Road			
				Rehabilitated Road		Bypasses	
	Parameter	Mean (*Std Deviation*)	Min/Max	Mean (*Std Deviation*)	Min/Max	Mean (*Std Deviation*)	Min/Max
Segments	Length [m] [a]	80.7 (*67.0*)	5/422	97.6 (*85.2*)	2/529	212.2 (*160.0*)	4/628
	Radius of horizontal curves [m] [b]	310.6 (*260.8*)	50/1200	252.2 (*184.6*)	90/900	600.9 (*432.9*)	120/1800
	Curve length [m] [b]	93.3 (*64.4*)	9/300	171.0 (*107.0*)	50.5/518.8	429.6 (*257.8*)	118.6/718.2
	Lane width [m] [a]	3.5 (*0.0*)	3.5/3.5	3.5 (*0.0*)	3.5/3.5	3.5 (*0.0*)	3.5/3.5
	Shoulder width [m] [a]	0.39 (*0.3*)	0.10/2.50	1.25 (*0.0*)	1.25/1.25	1.25 (*0.0*)	1.25/1.25
	Driveway density DD [driveways/mile] [a]	40.3 (*26.0*)	9.5/178.8	36.1 (*21.5*)	5.4/124.0	0.0 (*0.0*)	0.0/0.0
	Roadside Hazard Rating (RHR) [-] [a]	4.9 (*1.0*)	1/7	4.0 (*0.06*)	4/5	4.0 (*0.0*)	4/4
	Shoulder type [-] [a]	34% paved (186) 17% gravel (95) 46% turf (258) 3% composite (17)		100% paved (240)		100% paved (74)	
	Grades [%] [a] high (g > 6%) medium (3% < g ≤ 6%) low (g ≤ 3%)	8% high grade (23) 18% medium grade (49) 74% low grade (206)		6% high grade (7) 26% medium grade (31) 68% low grade (82)		14% medium grade (5) 86% low grade (32)	
Intersections	Typology [-] [c] 3ST (3 leg stop-controlled) 4ST (4 leg stop-controlled) 4SG (4 leg signalized)	84% 3ST (32) 3% 4ST (1) 5% 3SG (2) 8% 4SG (3)		88% 3ST (7) 12% 4ST (1)		No intersections along bypasses	
	Skew angle [°] [c]	21.5 (*20.2*)	0/60	15.6 (*15.4*)	0.0/45.0		
	Left-Turn Lanes [n° lanes] [c]	0.2 (*0.4*)	0/1	0.1 (*0.4*)	0/1		
	Right-Turn Lanes [n° lanes] [c]	0.2 (*0.4*)	0/1	0.4 (*0.5*)	0/1		
	Lighting [-] [c]	74% with lighting (28) 26% without lighting (10)		62.5% with lighting (5) 37.5% without lighting (3)			

[a] 278 segments for existing road, 157 segments for the redesigned road (120 on rehabilitated road and 37 on bypasses). [b] 158 curves for existing road, 91 curves for the redesigned road (69 on rehabilitated road and 22 on bypasses). [c] 38 intersections for existing road, and 8 intersections for the redesigned road (8 on rehabilitated road and 0 on bypasses).

5. Methods

To assess the efficiency of the redesign intervention described above, a predictive approach to safety analysis was employed. The predictive approach involved the use of a regression model to quantify the predicted number of accidents on each section of the infrastructure under consideration. The predictive model must be carefully calibrated for use in the specific study context. Calibration was based on knowledge of the specific characteristics of the area and state-of-the-art techniques. The calibrated model was then

used to simulate future scenarios and make projections to investigate the impact of the planned intervention. It was also possible to compare different future scenarios with different boundary conditions, such as different traffic volumes.

5.1. Model Description

The predictive model proposed by the HSM was adopted for this study. The regression model allowed us to determine the average crash frequency for a given site x as a function of the traffic volume (AADT) and its geometric–functional characteristics. The structure of the model is expressed by Equation (1), where $N_{predicted}$ is the predicted average crash frequency for a specific year for a site x; $N_{SPF\ x}$ is the predicted average crash frequency determined for 'base' conditions through the Safety Performance Function (SPF) for site x; $CMF_{i,x}$ is the Crash Modification Factor i to site x to adapt the specific geometric–functional features to 'base' conditions; and C_X is the Calibration Factor to adjust the SPF for local conditions of site x.

$$N_{predicted} = N_{SPF\ x} \cdot \left(CMF_{1,x} \cdot CMF_{2,x} \cdot \ldots \cdot CMF_{y,x}\right) \cdot C_X = N_{SPF\ x} \cdot CMF_{s,x} \cdot C_X \quad (1)$$

5.2. Segmentation

Since the predictive model is applied to each site, different sites must first be identified. Therefore, a segmentation process must be carried out on the analyzed road. Segmentation consists of dividing the road into intersections and segments. Moreover, segments are divided into smaller sections with homogeneous characteristics in terms of geometric-functional properties. Each site (i.e., each homogeneous segment or intersection) is then assigned the geometric–functional characteristics defined in Section 4.2.

The number of predicted crashes was calculated separately for roadway segments (rs) and intersections (i), using Equations (2) and (3), respectively.

$$N_{predicted,rs} = N_{SPF,rs} \cdot CMF_{rs} \cdot C_{rs} \quad (2)$$

$$N_{predicted,i} = N_{SPF,i} \cdot CMF_i \cdot C_i \quad (3)$$

5.3. Safety Performance Functions

Safety Performance Functions (SPFs) represent the shape of the model and allow the predicted number of accidents under 'base' conditions to be determined. The 'base' conditions are those for which all CMFs assume a value of 1, as will be discussed in Section 5.4. For roadway segments, the number of predicted crashes in the 'base' conditions calculated by the SPF depends on the traffic on the segment ($AADT$) and its length (L), as expressed in Equation (4). For intersections, the number of predicted crashes depends on the traffic on the main ($AADT_{maj}$) and secondary ($AADT_{min}$) roads, as reported in Equation (5). In the case of reduced traffic on the secondary road, it is possible to consider the total traffic ($AADT_{tot}$) as the sum of the traffic on the two roads, as indicated in Equation (6).

$$N_{SPF,rs} = f(AADT, L) \quad (4)$$

$$N_{SPF,i} = f\left(AADT_{maj}, AADT_{min}\right) \quad (5)$$

$$N_{SPF,i} = f(AADT_{tot}) \quad (6)$$

For rural two-way, two-lane roads, the SPFs shown in Table 3 [9,10], divided by severity level, were taken into account. The distinguishing of severity levels avoids the inclusion of Property Damage Only (PDO) crashes, which are not registered in Italy. In fact, KAB and KABC severity levels (fatal injury—K, incapacitating injury—A, non-incapacitating injury—B, possible injury—C) were considered. The adoption of alternative SPFs resulted in a different value of the predicted number of crashes per year for 'base' conditions on average over the 9-year period considered for the study. In fact, the values of the predicted

accidents in 'base' conditions shown in Table 3 were obtained by applying the SPFs to the actual road conditions with reference to the traffic values of the 9 years considered.

Table 3. Considered safety performance functions for different severity levels.

Facility Type		Severity Level	SPF—Safety Performance Function	N_{SPF}[crashes/year]
Segments *		**All**	$N_{SPF} = AADT \cdot L \cdot 365 \cdot 10^{-6} \cdot e^{(-0.312)}$	39.13
		KABC	$N_{SPF} = exp[-9.006 + 0.977 \cdot \ln(AADT) + ln(L)]$	14.64
		KAB	$N_{SPF} = exp[-8.499 + 0.852 \cdot \ln(AADT) + ln(L)]$	7.60
Intersections *	**3ST**	**All**	$N_{SPF} = \exp[-9.86 + 0.79 \cdot \ln\left(AADT_{maj}\right) + 0.49 \cdot \ln(AADT_{min})]$	66.39
		KABC	$N_{SPF} = \exp[-9.628 + 0.725 \cdot \ln\left(AADT_{maj}\right) + 0.312 \cdot \ln(AADT_{min})]$	14.08
		KAB	$N_{SPF} = \exp\left[-10.241 + 0.581 \cdot \ln\left(AADT_{maj}\right) + 0.468 \cdot \ln(AADT_{min})\right]$	5.58
	4ST	**All**	$N_{SPF} = \exp[-8.56 + 0.60 \cdot \ln\left(AADT_{maj}\right) + 0.61 \cdot \ln(AADT_{min})]$	4.08
		KABC	$N_{SPF} = \exp[-8.747 + 0.825 \cdot \ln(AADT_{tot})]$	0.40
		KAB	$N_{SPF} = \exp[-8.511 + 0.723 \cdot \ln(AADT_{tot})]$	0.19
	4SG	**All**	$N_{SPF} = \exp[-5.13 + 0.60 \cdot \ln\left(AADT_{maj}\right) + 0.20 \cdot \ln(AADT_{min})]$	4.81
		KABC	$N_{SPF} = \exp[-12.337 + 1.028 \cdot \ln\left(AADT_{maj}\right) + 0.231 \cdot \ln(AADT_{min})]$	0.21
		KAB	$N_{SPF} = \exp[-11.059 + 0.981 \cdot \ln(AADT_{tot})]$	0.13

* 278 homogeneous segments and 36 intersections (32 × 3ST, 1 × 4ST, 3 × 4SG).

Given the need to know the traffic on secondary roads at intersections, it is assumed to be equal to a percentage of the traffic on the main road. The value of the percentage is assumed in relation to the importance of the secondary road, as shown in Table 4.

Table 4. Assumption for minor road traffic at junctions.

Minor Road Importance	$AADT_{min}$
High	15% of $AADT_{maj}$
Medium–High	10% of $AADT_{maj}$
Medium	7.5% of $AADT_{maj}$
Medium–Low	5% of $AADT_{maj}$

5.4. Crash Modification Factors—CMFs

The crash prediction for 'base' conditions should be adapted to real site conditions by applying Crash Modification Factors (CMFs). CMFs assume different values as follows:

- $CMF > 1$, if site-specific conditions are worse than 'base' conditions;
- $CMF = 1$, if site-specific conditions are the same as 'base' conditions;
- $CMF < 1$, if site-specific conditions are better than 'base' conditions.

'Base' conditions in terms of geometric-functional road characteristics are defined both for segments and intersections. Different CMFs are defined with the relative 'base' conditions and data availability, as detailed in Table 5.

The CMF for each site is calculated whenever data are available according to HSM prescriptions [9]. When the mean CMF values are greater than 1, the conditions of the Italian roads are on average worse than the 'base' conditions of the US roads. In order to use the model to simulate future scenarios, the CMFs must be recalculated for the new traffic values and new geometric-functional characteristics. Average CMFs values for the existing road and the redesigned road are reported in Table 6. The most critical conditions for the existing road, in terms of geometric characteristics, were recorded for horizontal curvature and driveway density, which have the highest average CMFs values.

Table 5. CMFs for roadway segments and intersections of rural two-way two-lane roads with corresponding 'base' conditions and data availability for this study [9].

Facility Type	CMF	CMF Description	'Base' Conditions	Data Need for Calibration	Data Availability for This Study
Segments	CMF_{1r}	Lane width	12 feet	Required	Yes
	CMF_{2r}	Shoulder width	6 feet	Required	Yes
		Shoulder type	Paved	Required	Yes
	CMF_{3r}	Horizontal curvature	None ($R = \infty$)	Required	Yes
	CMF_{4r}	Vertical curvature	None	Desirable	No
	CMF_{5r}	Grade level	0%	Desirable	Yes
	CMF_{6r}	Driveway density (DD)	5 driveways per mile	Desirable	Yes
	CMF_{7r}	Centerline rumble strips	None	Desirable	No
	CMF_{8r}	Passing lanes	None	Desirable	No
	CMF_{9r}	Two-way left-turn lanes	None	Desirable	No
	CMF_{10r}	Roadside Hazard Rating (RHR)	3	Desirable	Yes
	CMF_{11r}	Lighting	None	Desirable	No
	CMF_{12r}	Automated speed enforcement	None	Desirable	No
Intersections (3ST, 4ST, 4SG)	CMF_{1i}	Intersection Skew Angle	0°	Desirable	Yes
	CMF_{2i}	Intersection Left-Turn Lanes	None	Required	Yes
	CMF_{3i}	Intersection Right-Turn Lanes	None	Required	Yes
	CMF_{4i}	Lighting	None	Required	Yes

Table 6. Comparison of average CMFs values for different scenarios.

Facility Type	CMF	CMF Description	Average CMF Value		
			Existing Road	Redesigned Road	
				Rehabilitated Road	Bypasses
Segments [a]	CMF_{1r}	Lane width	1.01	1.01	1.01
	CMF_{2r}	Shoulder width and type	1.22	1.09	1.09
	CMF_{3r}	Horizontal curvature	3.49	2.06	1.23
	CMF_{5r}	Grade level	1.03	1.04	1.01
	CMF_{6r}	Driveway density (DD)	1.39	1.34	1
	CMF_{10r}	Roadside Hazard Rating (RHR)	1.14	1.07	1.07
Intersections (3ST) [b]	CMF_{1i}	Intersection Skew Angle	1.09	1.07	-
	CMF_{2i}	Intersection Left-Turn Lanes	0.90	0.94	-
	CMF_{3i}	Intersection Right-Turn Lanes	0.97	0.94	-
	CMF_{4i}	Lighting	0.93	0.94	-

[a] 278 segments for existing road, and 157 segments for the redesigned road (120 on rehabilitated road and 37 on bypasses). [b] 32 intersections for existing road, and 7 intersections for the redesigned road (7 on rehabilitated road and 0 on bypasses).

The planned redesign, composed by the rehabilitated road and bypasses, shows safer characteristics in terms of horizontal curvature, shoulder type and width and roadside hazard rating. In fact, according to Table 6, the CMFs associated with these characteristics for the redesigned road are significantly reduced compared to the state of the art. It should also be noted that the bypasses are characterized by the absence of intersections and driveways.

5.5. Calibration Factor

Calibration was carried out to transfer the predictive model developed in the USA to the Italian context. The calibration factor (C_X) is computed as expressed in Equation (7).

$$C_X = \frac{\sum_{\substack{all \\ sites}} N_{observed}}{\sum_{\substack{all \\ sites}} N_{predicted\ n.c.}} \quad (7)$$

where $N_{observed}$ is the number of observed crashes for each site; $N_{predicted\ n.c.}$ is the number of predicted crashes through the regression model (not calibrated), calculated by Equation (8):

$$N_{predicted\ n.c.} = N_{SPF\ x} \cdot CMF_{s,x} \quad (8)$$

A different value of C_X was calculated for each type of facility with the aim of obtaining a value closer to 1. In fact, the calibration factor is greater than one if the model tends to underestimate the number of accidents compared to those actually observed or, conversely, it is less than one if the model tends to overestimate reality. The results of the calibration are shown in Table 7. It should be noted that these values are the result of the application of the model to the state of the art. In fact, only data for existing road are available on the number of accidents that have occurred, and thus it is possible to calibrate.

Table 7. Calibration factor for different SPFs (severity levels).

Facility Type		Severity Level	$N_{pred,\ n.c.}$ [crashes/year]	N_{obs} [crashes/year]	C_X
Segments *		All	110.97	17.56	0.16
		KABC	41.52		0.42
		KAB	21.57		0.81
Intersections *	**3ST**	KAB	4.98	6.22	1.25
	4ST	KAB	0.11	0.22	2.00
	4SG	KAB	0.34	0.56	1.63

* 278 homogeneous segments and 36 intersections (32 × 3ST, 1 × 4ST, 3 × 4SG).

As the best fit for the segments calibration is obtained for the severity level KAB, with a C_X closer to 1, only KAB is considered for the intersections. This approach is adopted because the number of segments was greater than the number of intersections and, thus, segments are considered more reliable.

5.6. Goodness-of-Fit Measures

In order to optimize the calibration process and ensure the reliability and representativeness of the model, a number of parameters for estimating the Goodness-of-Fit (GOF) were evaluated (as suggested by the literature [47]). The following parameters were considered:

- Coefficient of Variation (CV);
- Mean Absolute Deviation (MAD);
- Dispersion parameter (k);
- % CURE deviation (% $CURE\ dev$).

Therefore, starting from the full dataset available, different selection criteria were applied to filter the input data for calibration and to improve the GOF. Notably, to enhance the calibration process, reference was only made to the KAB severity level, which showed the best results, as illustrated in Section 5.5. Furthermore, for the intersections, the calibration was optimized only for the 3ST type, as it had a sufficient number of data. The following scenarios were considered:

- Segments:
  - Case 1.RS: all available data for roadway segments were taken into account;
  - Case 2.RS: from all available data, only segments with $CMF_{rs} < 10$ and a length greater than 0.014 miles were considered;
  - Case 3.RS: from all available data, only segments with $CMF_{rs} < 10$ and a length greater than 0.020 miles were considered;
  - Case 4.RS: from all available data, only segments with $CMF_{rs} < 10$ and a length greater than 0.023 miles were considered.
- Intersections:

- Case 1.I: all available data for 3ST intersections were taken into account;
- Case 2.I: all available data for 3ST intersections except one intersection (which showed a large discrepancy between the predicted and observed number of crashes) were included.

The targeted exclusion of specific elements that show an unusual trend makes it possible to improve the GOF. In fact, the results (Table 8) show that filtering the input data reduces the GOF estimation parameters. In particular, the aim is to reduce the %CURE deviation to values below 5%, as suggested in the literature [47]. To this purpose, it is necessary to remove some very short segments where the observed number of accidents is zero against a predicted number of accidents greater than zero. Finally, after the calibration optimization, Case 4.RS was considered for segments and Case 2.I for intersections. Thus, the calibration factor was 0.79 and 1.12 for segments and intersections, respectively. This will allow the model to be employed to simulate future scenarios to assess the effectiveness of specific intervention measures. Consequently, the level of confidence associated with the simulated future scenarios depended on the GOF parameters obtained from the selected calibration cases.

Table 8. Calibration results in terms of calibration factor and GOF parameters for different scenarios.

Facility Type	Case	$N_{pred,\,n.c.}$ [crashes/9 years]	N_{obs} [crashes/9 years]	C_X	*CV*	*MAD*	*k*	*% CURE dev*
Segments	**Case 1.RS**	196.30	158	0.80	0.18	0.70	0.081	25%
	Case 2.RS	165.15	134	0.81	0.17	0.67	0.069	4%
	Case 3.RS	159.61	129	0.81	0.16	0.74	0.056	2%
	Case 4.RS	153.14	121	**0.79**	0.15	0.73	0.048	1%
Intersections (3ST)	**Case 1.I**	46.42	56	1.21	0.32	1.71	1.059	9%
	Case 2.I	45.68	51	**1.12**	0.32	1.59	0.942	3%

5.7. Simulation of Future Scenarios

Once the model is calibrated to the study context, it is employed to simulate future scenarios. In particular, two future scenarios were simulated:

- **Scenario A**: no intervention is carried out and the safety performance of the existing road under future traffic conditions is to be assessed;
- **Scenario B**: the redesign of the existing road, consisting of road rehabilitation and the implementation of bypasses is considered.

To simulate future scenarios, it is assumed that the traffic on the road would be equal to the average traffic of the last two available years (2021 and 2022). In Scenario A, all traffic travels on the existing route. It is assumed that the traffic varies in constant steps between the known traffic sections. Thus, eight constant traffic zones were identified, as shown in Figure 2.

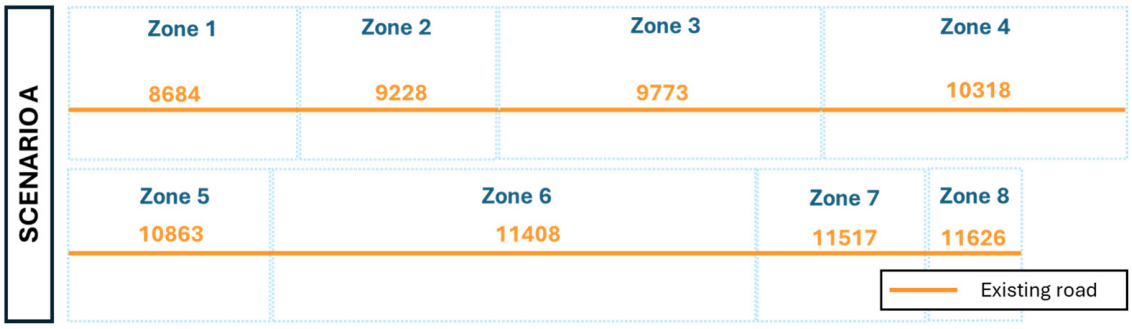


Figure 2. Traffic zones for Scenario A.

With reference to Scenario B, in the presence of the variant, part of the traffic will travel on the existing route and the remaining traffic will travel on the bypasses. The portion of traffic that will affect each of the five bypasses is assumed according to the specific bypassed area. In particular, the entity of traffic traveling on the existing route through residential areas is assumed in relation to the area extension, while the remaining traffic is assumed to be diverted to the bypasses, as shown in Table 9.

Table 9. Assumed percentage redistribution of traffic between bypass and existing road in residential areas.

Bypass	Surface of the Bypassed Residential Area [m^2]	% of Traffic on Bypass	% of Traffic on Existing Road
Bypass 1	1,133,955	75%	25%
Bypass 2	29,038	97.5%	2.5%
Bypass 3	267,420	95%	5%
Bypass 4	816,896	80%	20%
Bypass 5	700,797	85%	15%

The traffic distribution scheme assumed for Scenario B is illustrated in Figure 3.

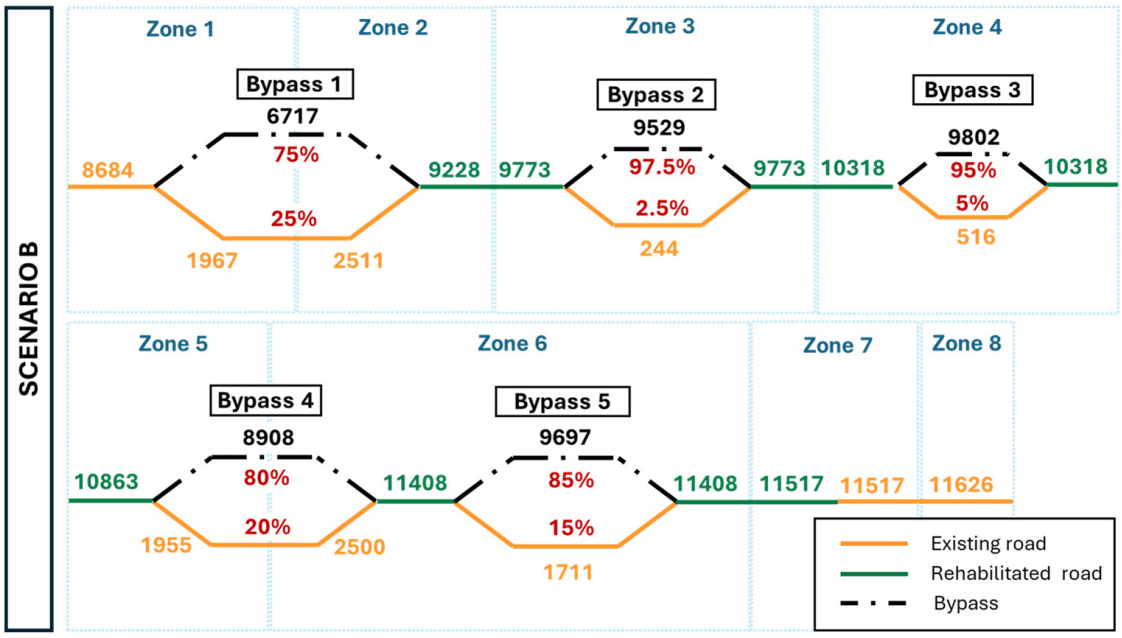


Figure 3. Traffic distribution diagram between rehabilitated road and bypasses for Scenario B.

6. Results and Discussion

6.1. Road Redesign Effectiveness

Adopting the predictive model to the two future scenarios, the number of predicted accidents was obtained (Table 10). For scenario A, approximately 22 accidents per year were predicted, distributed between segments and intersections. For Scenario B, the total number of predicted crashes was obtained by adding the predicted crashes on bypasses and existing or rehabilitated road sections. Although the bypasses account for a significant proportion of traffic (always more than 75% of the total), the number of accidents predicted on the bypasses are about 20% of the total for Scenario B. This highlights the importance of low-curvature road layouts with absence of driveways. Overall, the reduction in the number of predicted accidents is estimated to be around 10 accidents per year. This represents a reduction of 45% on the total crashes predicted with respect to Scenario A. This estimate confirms the usefulness in terms of safety of the bypasses and road rehabilitation.

Table 10. Number of predicted crashes for future scenarios.

Number of Predicted Crashes [crashes/year]		Scenario A	Scenario B		
		Existing Road	Existing Road	Rehabilitated Road	Bypasses
Segments	$N_{predicted,rs}$	16.64	1.84	6.20	2.30
Intersections	$N_{predicted,i}$	5.34	0.32	1.35	-
Total	$N_{predicted,tot}$	21.98		12.02	
Yearly crash reduction				**9.96**	
% crash reduction				**45%**	

6.2. Effect of Traffic Redistribution

Alternative future scenarios were simulated to assess the potential impact of a different traffic distribution to that assumed in Scenario B (Figure 3). The alternative scenarios considered a different use of the bypasses in terms of the portion of traffic using them compared to the total for each section. The scenarios described in Table 11 were taken into account, starting from the most favorable Scenario B1, where all traffic takes the bypasses, to the least favorable Scenario B9, where all traffic remains on the existing route.

Table 11. Assumed traffic redistribution for alternative scenarios.

Scenario	% of Traffic on Bypasses	% of Traffic on Existing Road
B1	100%	0%
B2	95%	5%
B3	90%	10%
B4	80%	20%
B5	70%	30%
B6	60%	40%
B7	50%	50%
B8	25%	75%
B9	0%	100%

Simulations have shown that the predicted number of accidents can be reduced by between 23% and 53% by varying the proportion of traffic using bypasses, as shown in Figure 4. This is because even if no vehicles use the bypass (Scenario B9), there is still a safety benefit from the road layout rehabilitation.

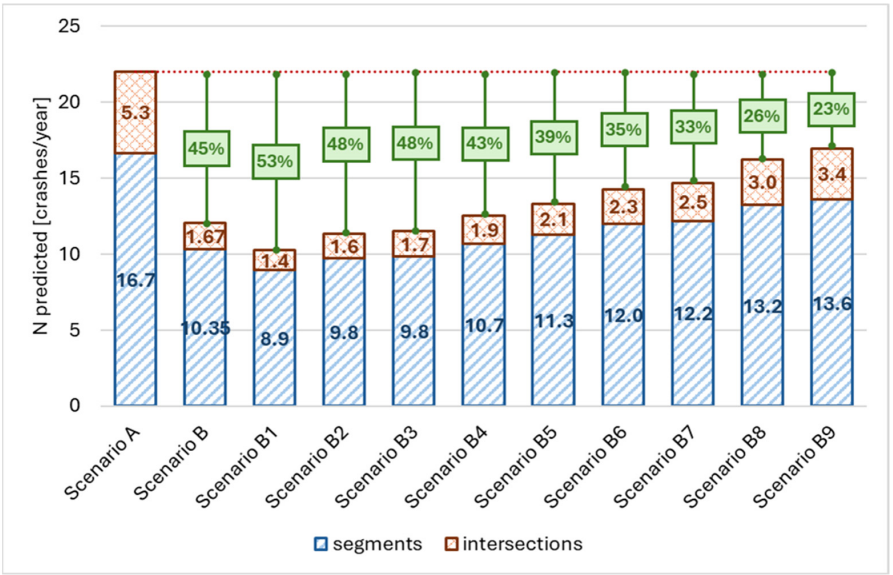


Figure 4. Effect of traffic redistribution on crash reduction.

6.3. Effect of Traffic Variation

The impact of a possible increase or decrease in total road traffic was also taken into account. This allowed us to assess the sensitivity of the infrastructure to possible future variations and the resilience of the planned intervention. An increase/decrease in traffic of ±20% (in intervals of 5 to 10%) compared to the value initially assumed for the simulation of Scenarios A and B was considered. The results are illustrated in Figure 5. It can be seen that the sensitivity to traffic is lower in the case of Scenario B (with redesign intervention). In fact, the overall number of predicted accidents on segments and intersections is lower independently from a traffic increase/decrease. Moreover, the slope of the trend line expressing the crashes increase with increasing traffic is lower. This means that the implementation of rehabilitations and bypasses make the infrastructure more resilient and less vulnerable to potential traffic variation.



Figure 5. Effect of traffic variation on crash trend.

In fact, this sensitivity analysis describes the influence of traffic volume on the number of predicted crashes and, thus, on the effectiveness of the redesign intervention. A similar approach can be adopted to assess the impact of the other variables of the predictive model (e.g., curve radius, lane width, shoulder width and type), affecting the CMFs values. This additional sensitivity analysis could be the scope of a further agenda.

6.4. Applications, Limitations, and Future Developments

The presented case study shows the potential of predictive models in road rehabilitation/maintenance management. In fact, the predictive model allowed the quantification of the benefits of the planned intervention in terms of accident reduction. It can be concluded that this method can be used in the decision-making process to identify the best intervention alternative to be implemented. To this end, it would be appropriate to extend the model to the level of the entire managed network to determine where, when and how it is most appropriate to intervene. Obviously, this requires a large database on the characteristics of the road infrastructure, traffic, and the number of accidents. In addition, the model should be recalibrated over a wider geographical area to be suitable for application on a larger scale. Conversely, the model calibrated on a section of road with sufficiently homogeneous characteristics can only be adopted on the road itself or on roads with similar characteristics.

7. Conclusions

The purpose of this case study was to evaluate the impact of a redesign intervention consisting of the construction of bypasses to avoid residential areas and the partial adjustment of the existing route. Bypasses are sections of road characterized by sufficiently large curve radii and the absence of intersections or direct accesses to the road. At the same time, the existing route is partially rectified and existing driveways are reorganized and optimized. Predictive models were used to quantify the expected benefit of such interventions. As expected, the CMFs describing the characteristics that were modified, such as radii of curvature, driveway density, shoulder type and width, were significantly reduced for the future scenario in the presence of intervention compared to the state of the art. CMFs enable the benefits of any change in infrastructure characteristics to be quantified. The model is then used to simulate two future scenarios: Scenario A in the absence of intervention and Scenario B in the presence of intervention. By comparing the results obtained, it is possible to quantify the benefit of the intervention as the annual reduction in the number of predicted accidents. A reduction of about 10 accidents per year was therefore estimated, which corresponds to a reduction of around 45% of the total number of accidents without intervention. As this simulation was based on one possible assumption of the use of bypasses in terms of the portion of traffic passing through them, it was decided to evaluate other alternative scenarios. These alternative scenarios considered different bypass utilization rates. It was shown that even in the worst case of no bypasses being used (0% of traffic using them), there would still be a 23% reduction in accidents as a result of the rehabilitation of the existing route. In addition, in the most favorable case, where the number of vehicles using the bypass is higher than initially estimated, a reduction in accidents up to 53% could be achieved.

In addition, since the initial simulations assumed future traffic to be equal to the average of the last two years available (2021–2022), it was chosen to assess the impact of a possible general increase or decrease in traffic. The results show that as the traffic changes, the scenario with the presence of the intervention still allows a reduction in the number of predicted accidents. Furthermore, this reduction is more pronounced as traffic increases. This means that if traffic increases in the future without any intervention, there would be a more severe condition. In fact, the presence of redesign intervention allows an increasing benefit with traffic. Therefore, it can be said that the intervention will result in a clear benefit, and that it has a reasonable degree of resilience to possible variations in boundary conditions, such as traffic.

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