Chapter

Analytical Assessment of Effective Maintenance Operations on At-Grade Unsignalized Intersections

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Abstract

This chapter describes a methodological structure to support and improve the decision-making process for redesigning the geometric configurations of substandard sites and thus reduce crash risk factors on at-grade three-leg and four-leg intersections with stop-control on minor roads and single-lane roundabouts belonging to a two-lane rural road network located in Southern Italy. Starting from an initial evaluation of the risk level at each investigated site and adopting a procedure developed by the Italian National Research Council based on an estimated crash rate level, a more precise hierarchy of intersections with "black" rankings was developed. In addition, new geometric configurations for the most hazardous sites were suggested based on a statistical comparison in terms of safety and Level of Service (LoS). The effectiveness of the strategies was validated by computing the expected LoS and safety by adopting an empirical Bayesian analysis and performance functions centered on a revised Highway Safety Manual procedure reflecting the context of the study.

Keywords: risk assessment, reducing crash risk levels, level of service

1. Literature review

The key role played by transportation networks in social well-being and safeguarding the world economy means priorities must be established to maintain an adequate level of service and functionality and adequately managing existing weak areas as well as possible hazardous events: a thorough examination of activities within the system, potential risks for users, and the careful management of the planning phase of controls and maintenance operations can help reduce, if not even prevent, failures in the system that may compromise good operation and endanger health, safety, and the environment.

Dickey and Santos [1] identified the response time of emergency services during hazardous events in the transportation system—one of the fundamental actions in restoring disrupted infrastructures—and in guaranteeing essential levels of service and safety to users.

Freiria et al. [2] considered the road transport system as one of the most critical infrastructures in hazard situations performing an LRSRM model (Local Regional

Scale Risk Model) to identify the most significant roads from the multiscale perspective, which should guarantee better operability of the sites and help allocate local resources better during hazardous events.

European Directive 2008/96/EC [3] on road safety stressed the central role of risk analysis and management as activities that help ensure the good functioning of a road network, defining road infrastructures as the third pillar of safety policy.

Many scholars [4–6] focusing on the road hotspots identified in the light of European Directive objectives suggested calculating crash frequencies and crash rates to rank "black" sites, while others suggested adopting the empirical Bayes (EB) approach and the full Bayes (FB) approach in combination with the previous measures.

The main reason for using a Bayesian approach is to force the analyst to look at historical data sets or to canvass expert knowledge to determine what is known about the parameters and processes [7–9]. The key difference between Bayesian statistical inference and frequentist statistical methods concerns the nature of the unknown parameters. In the frequentist framework, a parameter of interest is assumed to be unknown, but fixed. In the Bayesian view of subjective probability, all unknown parameters are treated as uncertain and therefore should be described by a probability distribution. Replication is an important and indispensable tool [10], and Bayesian methods fit within this framework because background knowledge is integrated into the statistical model.

Xie et al. [11] worked out a procedure to identify hotspots in a road network, also investigating different contributing factors to road pedestrian safety such as vehicle volumes, road networks, land use, demographic and economic features, and the social media. The researchers identified potential "black" sites by estimating crash costs, considered an accurate safety measure well able to reflect injury severity levels.

2. Goals definition

Analysis procedure presented here focuses on intersections: crossing and turning maneuvers create opportunities for vehicle-vehicle, vehicle-pedestrian, and vehicle-bicycle conflicts that may also result in traffic crashes. Certainly, human error is a contributing factor to road crashes; however, in addition to driver behavior, road engineering and design measures can also make intersections safer.

The work phases are shown in **Figure 1**.

In particular, the research steps are summarized as follows:

a. Evaluating a first measure of exposure to crash risk by using a procedure developed by the Italian National Research Council [12], shown in detail in Section 3.1 and in **Figure 3**, it is useful in ranking black intersections.

b. Computing LoS, determined by ascertaining control delay at each maneuver and estimating crash costs. Delays were assessed by revising specific analytical HCM 2016 [13] models on the basis of field measurements (see Section 3.2 for details). The crash cost estimates were obtained from the mean values of the costs for injuries to people and damage to vehicles made available by the Italian Ministry of Infrastructures and Transport.

c. Identifying hotspots: working in accordance with European Directive 2008/96/EC on road safety, the most dangerous intersections where high crash rate, high crash cost, and low-medium LoS were observed (hotspots) were analyzed in greater depth.

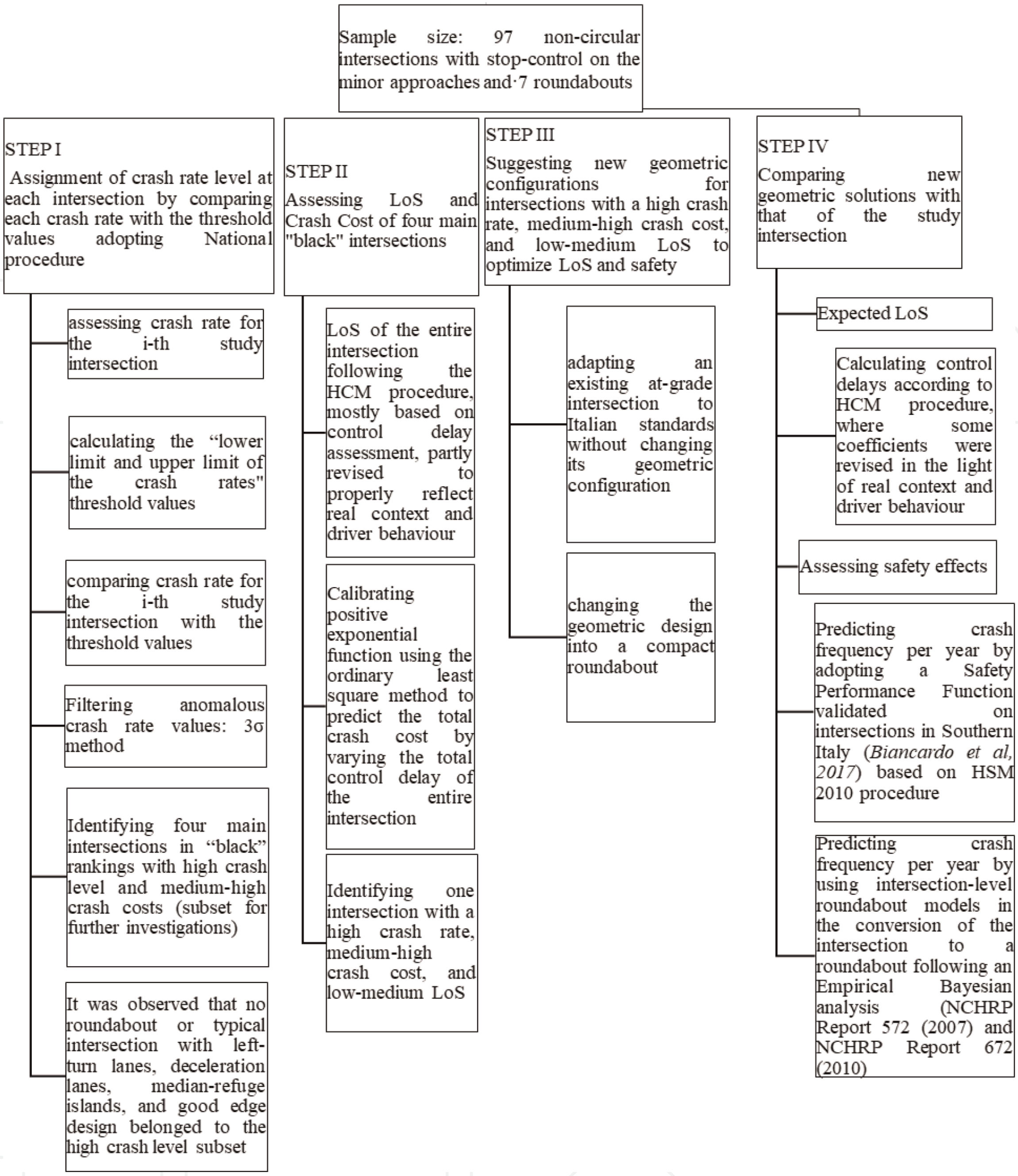


Figure 1.
Methodological approach to plan safer strategies at intersections.

d. Identifying driver risk factors at hotspots by focusing on the mismatch between geometric design for each intersection and the requirements of the Italian Design Standard (Norme funzionali e geometriche per la costruzione delle intersezioni stradali, GU n. 70 del 24-7-2006) [14]; poor matching of the real configuration with the design requirements is reflected in greater consequent exposure to crash events and a lower level of service.

e. Managing risk levels at hotspots by hypothesizing structural adjustments keeping traffic features and environmental conditions constant. Two adjustments were proposed:

- Adjusting the current geometric design to the Italian Design Standard without changing the configuration [15, 16].

- Modifying the configuration into a roundabout to achieve benefits in terms of a reduction of conflict points, vehicle speed reduction around the central island, and pedestrian safety [5, 17, 18].

f. Assessing the effectiveness of risk management: comparing before and after configurations of the hotspots by calculating the expected LoS and the expected safety effects in terms of crash frequency.

In greater detail, the expected LoS effects were calculated following HCM2016 procedure, but revising, in the light of measurements obtained at study sites; on the other hand, the expected computation of safety effects was performed by adopting the Safety Performance Function (SPF) introduced in [16] according to Highway Safety Manual (HSM) 2010 [17] procedure but revised in the light of study carried out in Southern Italy to which the intersections investigated here belong. Calculation of the expected safety effects obtained from converting the intersections to roundabouts was performed by (a) adopting the analytical models proposed in Rodegerdts et al. [18, 19], whose calibration conditions fit the study context presented here and (b) by using EB analysis to quantify the positive advance of intervention, a common statistical practice in the scientific literature.

This book chapter is organized as follows: Section 2 focuses on data collection, while Section 3 focuses on data analysis for evaluating measures that reflect the exposure of sites to crash risk; the results of the case study are displayed and discussed in Section 4.

3. Data collection

The crash data used involved 104 intersections belonging to two-lane rural roads in Southern Italy located in a flat area with a vertical grade of less than 5%, that is, 97 non-circular intersections before the Italian Road Design Standard [20] became law and seven single-lane roundabouts were built.

The road surface of the intersection area is paved, and neither space for pedestrian and bicycle use nor space to park vehicles exists by the roadside. In particular, 10% of the typical intersections have exclusive left-turn lanes, a sufficient sight distance for drivers at a stop-controlled or yield-controlled approaches, an acceptable entry and exit edge radius, and a median-refuge island along the legs. Almost all intersections have right-turn lanes on major-road approaches. The mean value of the approaching lane width and departing lane width is 2.70 m, and the average value of the entry and exit radius is 8 m; the average speed on the road segments belonging to the major roads approaching the intersections is around 70 km/h on a road Section 150 m from the intersection area, while on the minor road, it is approximately 45 km/h at the control section and 150 m from the intersection area.

All the single-lane roundabouts analyzed here are of the modern type. There are three conventional roundabouts with an inscribed circle diameter of between 40 and 50 m, three compact roundabouts with an inscribed circle diameter of between 25 and 40 m, and one mini-roundabout with an inscribed circle diameter of between 14 and 25 m. All the roundabouts have one entry lane for each approach as well as for the exit lanes of all the departures with an average entry and exit width of 3.00 m; the circulatory roadway has no lane markings, and the average width is 6.00 m. The circular central island is not practicable, and the average width is 4.00 m. The length of the splitter islands is almost 3.50 m, and the average width is 1.50 m. The average entry radius is 15 m with an exit radius of 25 m. The distance between an entry lane and the first exit lane for the next leg is at least 10 m.

The main features of each crash as identified by analyzing the crash reports were as follows: the location where the crashes happened, the number of crashes, injuries, and fatalities, type of crash, type, and number of vehicles involved, road surface conditions, lighting conditions, marking conditions, the number of legs and lanes, lane width, $AADT_{maj}$, that is, the AADT on major roads in terms of vehicles per day, and $AADT_{min}$, that is, the AADT on minor roads in terms of vehicles per day, the presence of left-turn lanes, median-refuge islands, right-turn lanes, and the diameter of the roundabouts.

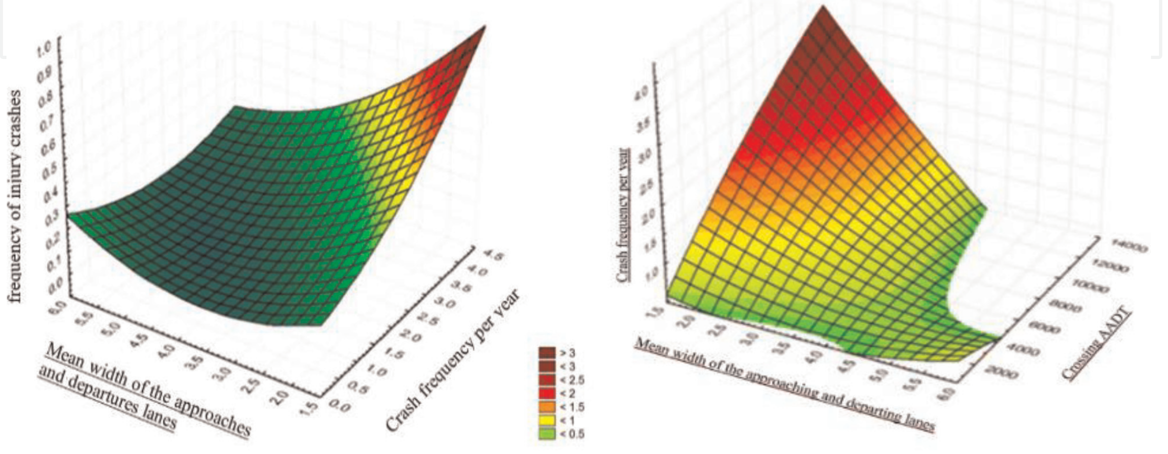
A total of 827 crashes were recorded in 5 years. The geometric features of each investigated intersection (see **Table 1**) were established from documents made available by the Regional Administrative Offices. A total of 770 crashes were observed at non-circular intersections, 623 of which were injury crashes, and 147 involved property damage only (PDO) crashes; a total of 1025 injuries were recorded at non-circular intersections, and 12 fatalities occurred. A total of 57 crashes were observed at single-lane roundabouts, of which 36 were injury crashes and 21 PDO crashes; a total of 57 injuries were recorded at single-lane roundabouts, and no fatalities occurred.

The crash value for each intersection shows the number of crashes over a 5-year study period, while the frequency of injury crashes refers to the number of injury crashes per year at each intersection during the study period. **Figure 2a** shows that

Features at intersection	**Non-circular intersections**				**Roundabouts**			
	Min	**Mean**	**Max**	**C.V.**	**Min**	**Mean**	**Max**	**C.V.**
Total number of crashes	3	4.51	10	0.84	1	1.32	5	0.75
Total number of injury crashes	0	0.99	6	0.79	0	0.86	2	0.44
Number of injuries	0	1.61	7	0.97	0	1.32	4	0.89
Frequency of crashes per year	0.33	0.48	4.33	0.81	0.12	0.18	0.82	0.77
Frequency of injury crashes per year	0	0.22	1.38	0.79	0	0.10	0.13	0.66
Frequency of injuries	0	0.28	2.00	0.93	0	0.21	0.5	0.87

Note: Min—minimum value; Mean—average value; Max—maximum value; C.V.—coefficient of variation, equal to the standard deviation divided by the mean value.

Table 1.
Overview of the main statistical features of the crashes and the intersection type.



a) *b)*

Figure 2.
Hazard maps of injury crash frequency. (a) Crashes vs geometric properties of lanes. (b) Crashes vs traffic and geometric properties.

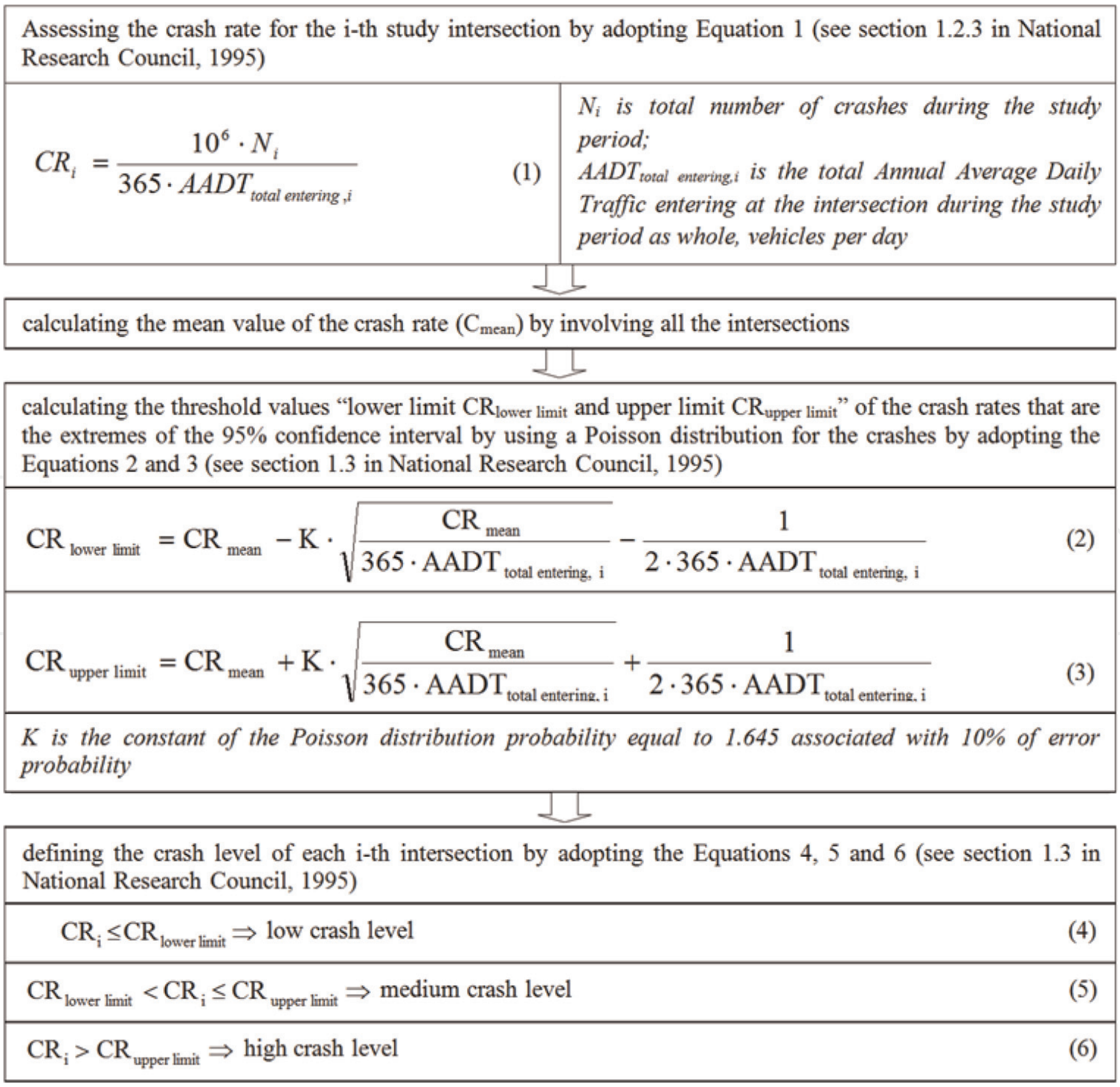
injury crash frequencies per year increase when the total crash frequency per year increases and the mean width of the approaching and departing lanes of the regular intersections decreases. **Figure 2b** shows how crash frequencies per year increase when the AADT crossing the intersection increases and when the mean width of the approaching lane to an intersection or departing lane from the intersection decreases.

4. Data analysis: evaluating measures reflecting crash risk exposure

4.1 Calculating crash rate at intersections as a first measure of safety level

In the light of the research goals set out in Section 1 and shown in **Figure 1**, a procedure developed in 1995 by the Italian National Research Council [12] was used to assess the safety level of traffic conditions at each ith intersection investigated, as shown in the flowchart in **Figure 3**.

Before computing the crash safety level, LoS and total crash cost, a technique for filtering anomalous crash rates was adopted using the 3σ method. The method is based on the calculation of the standard deviation (σ) and mean values (μ) for crash rate distribution to check the homogeneity of scattering around the average and the



Assessing the crash rate for the i-th study intersection by adopting Equation 1 (see section 1.2.3 in National Research Council, 1995)

$$CR_i = \frac{10^6 \cdot N_i}{365 \cdot AADT_{total\ entering,i}} \qquad (1)$$

N_i is total number of crashes during the study period;
$AADT_{total\ entering,i}$ is the total Annual Average Daily Traffic entering at the intersection during the study period as whole, vehicles per day

calculating the mean value of the crash rate (C_{mean}) by involving all the intersections

calculating the threshold values "lower limit $CR_{lower\ limit}$ and upper limit $CR_{upper\ limit}$" of the crash rates that are the extremes of the 95% confidence interval by using a Poisson distribution for the crashes by adopting the Equations 2 and 3 (see section 1.3 in National Research Council, 1995)

$$CR_{lower\ limit} = CR_{mean} - K \cdot \sqrt{\frac{CR_{mean}}{365 \cdot AADT_{total\ entering,\ i}}} - \frac{1}{2 \cdot 365 \cdot AADT_{total\ entering,\ i}} \qquad (2)$$

$$CR_{upper\ limit} = CR_{mean} + K \cdot \sqrt{\frac{CR_{mean}}{365 \cdot AADT_{total\ entering,\ i}}} + \frac{1}{2 \cdot 365 \cdot AADT_{total\ entering,\ i}} \qquad (3)$$

K is the constant of the Poisson distribution probability equal to 1.645 associated with 10% of error probability

defining the crash level of each i-th intersection by adopting the Equations 4, 5 and 6 (see section 1.3 in National Research Council, 1995)

$$CR_i \le CR_{lower\ limit} \Rightarrow \text{low crash level} \qquad (4)$$

$$CR_{lower\ limit} < CR_i \le CR_{upper\ limit} \Rightarrow \text{medium crash level} \qquad (5)$$

$$CR_i > CR_{upper\ limit} \Rightarrow \text{high crash level} \qquad (6)$$

Figure 3.
Assessment of the crash safety level of each ith study intersection.

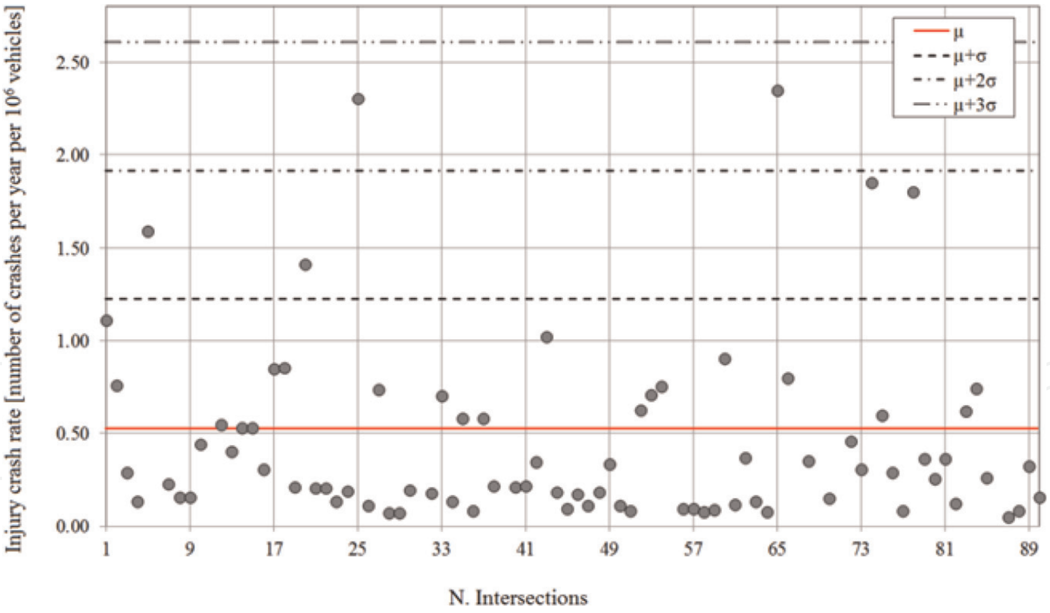


Figure 4.
Control charts of the crash rate values for typical intersections.

maximum deviation at 3σ. **Figure 4** shows an example of the control chart of the crash rates for non-circular intersections throughout the study period. It can be observed how 92% of the measurements fall within the range [0; μ + σ] = [0; 1.24], 97% fall within the range [0; μ + 2σ] = [0; 1.94], and all the values fall within the range [0; μ + 3σ] = [0; 2.64]. $CR_{\text{lower limit}}$ is equal to 0.36 crashes per year per 10^6 vehicles crossing the i^{th} intersection, and $CR_{\text{upper limit}}$ is equal to 0.52 crashes per year per 10^6 vehicles crossing the i^{th} intersection.

The overall results show that 63% of the total number of intersections indicate a low crash level (a total of 51 non-circular intersections and 7 single-lane roundabouts); 33% show a high crash level (a total of 34 non-circular intersections), and the remaining 4% represents a medium crash level (four non-circular intersections).

4.2 Calculating level of service as a second measure of safety level

The next step in the study focused on assessing LoS and crash costs for the four intersections where a high crash level and medium-high crash cost were observed. Neither the non-circular intersections respecting the Italian Road Design Standard nor the roundabouts are included among the "black" rankings. **Figure 5** shows an excerpt of the current geometric design of four "black" ranking intersections.

Table 2 shows the main features of the investigated intersections mentioned above: the number of legs, $AADT_{maj}$, $AADT_{min}$, and CR_i, as well as the total number of crashes, the total number of injuries, and the total number of vehicles damaged during the collision. **Table 3** shows the distribution of the hourly traffic flow (q_j) for the equivalent passenger cars in the different travel directions as illustrated in **Figure 5**.

The geometrical configuration of the four study intersections in **Figure 5** is very simple, and no additional geometric modules exist to promote safe maneuvering, according to the specifications in Section 2. This is the opposite of what happens at intersections where a "low crash level" was observed, where additional modules exist, and where geometric features respect the Italian Road Design Standard requirements in full. LoS was assessed for the entire intersection by evaluating control delay dj for each maneuver j^{th}. The HCM2016 [13] defines control delay as the measure of effectiveness used to set LoS at TWSC intersections as perceived by users.

Intersection **A** Intersection **B**

Intersection **C** Intersection **D**

Figure 5.
The geometric design of the currently non-circular intersections studied.

Site	Number of legs	$AADT_{maj}$,	$AADT_{min}$,	CR_i	Number of		Total number of
					Crashes	Injuries	Vehicles damaged during collision
		vpd	vpd		5-year study period		
Intersection A	3	3163	2120	2.22	4	3	4
Intersection B	4	3518	3153	1.32	11	4	9
Intersection C	3	6193	3097	1.72	12	8	7
Intersection D	4	4112	3102	2.09	14	4	6

Table 2.
Overview of the crash and traffic features of four typical intersections investigated.

The analytical model (Eq. (7)) adopted to estimate average control delay d_j per maneuver j^{th} refers to Eqs. (17)–(38) of HCM2016 [13] and assumes that there is no residual queue at the start of the analysis period. In most cases, the recommended analysis period is 15 min.

$$d_j = \frac{3600}{C_{e,j}} + 900 \cdot T \left[\frac{q_j}{C_{e,j}} - 1 + \sqrt{\left(\frac{q_j}{C_{e,j}} - 1 \right)^2 + \frac{\frac{3600}{C_{e,j}} \cdot \frac{q_j}{C_{e,j}}}{450T}} \right] + 5 \tag{1}$$

Site	Traffic volume, vph				Site	Traffic volume, vph				
Intersection **A**	Direction	X	Y	Z	Intersection **B**	Direction	X	Y	Z	W
	X	—	226	13		X	—	150	60	60
	Y	170	—	68		Y	100	—	70	100
	Z	70	11	—		Z	70	90	—	80
						W	100	30	110	—
Intersection **C**	Direction	X	Y	Z	Intersection **D**	Direction	X	Y	Z	W
	X	—	374	42		X	—	150	60	80
	Y	274	—	190		Y	180	—	70	80
	Z	142	90	—		Z	70	40	—	60
						W	30	50	80	—

Table 3.
Distribution of the hourly traffic volume in the subject lane per maneuver.

where q_j is the flow in the subject lane for maneuver j, in vph; $C_{e,j}$ is the effective capacity of the subject lane for maneuver j, in vph; T is the time period, in hours (T = 1 for a 1-h analysis, T = 0.25 for a 15 min analysis); and 5 is the waste time during the deceleration and acceleration phases compared with free flow speed, expressed in seconds (5 s).

Eq. (7) was adjusted for the real context working on one of the main variables: effective capacity $C_{e,j.}$

$C_{e,j}$ was calculated by adopting real measurements of $t_{c,j}$ (critical gap per maneuver j-th) and $t_{f,j}$ (follow-up time per maneuver j-th) values at the four study intersections shown in **Figure 5** instead of adopting the HCM2016 equation based on studies across the United States.

The evaluation of $t_{c,j}$ critical gaps is not immediate and can appear difficult to estimate from a field measurements sample; results of empirical studies have shown that different combinations of configuration and situational influences may lead to diverse profiles of compliance and proactive safety behavior among drivers [21].

In the literature, several techniques exist to calculate gap acceptance data assuming the consistency of road drivers, for example, the Raff and Hart method [22], the Drew-Dawson method [23–25], and the stepped line model.

As a result, the $t_{c,j}$ value for each driver entering an intersection from a minor road in **Figure 5** was calculated using the Drew-Dawson method, based on the median time value. **Figure 6** shows an example of critical gaps ($t_{c,j}$) for drivers crossing intersection A (see **Figure 5**) turning from leg Y to leg Z (left turn from minor to major road) and from leg Z to leg Y (right turn from minor to major road) during time period T. **Table 4** shows an overall view of the observed values of the $t_{c,j}$ and $t_{f,j}$ variables for the maneuvers at intersection A.

The control delay for an entire intersection $d_{entire\_intersection}$ (see Eq. (8)) is calculated by computing a weighted average of the control delay for each maneuver d_j, weighted by the volume of each flow for the maneuver investigated.

$$d_{entire\ intersection} = \frac{\sum d_j q_j}{\sum q_j} \tag{2}$$

According to the thresholds defined in HCM2016 [13], the LoS was defined for each maneuver by also associating qualitative measures from A (control delay between 0 and 10 s/veh) to F (control delay more than 50 s/veh) as provided in

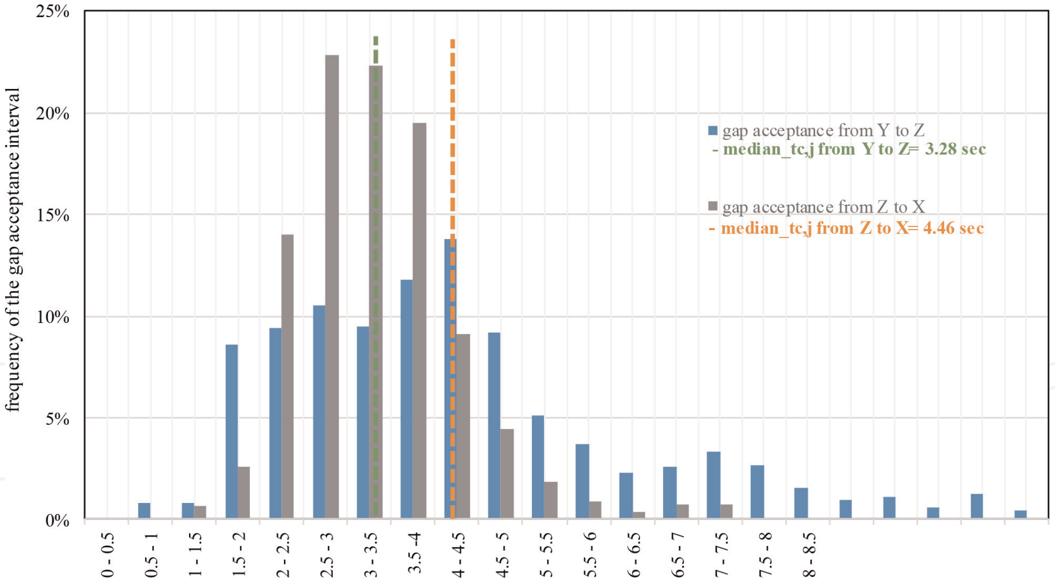


Figure 6.
Example of $t_{c,j}$ assessment using the Drew-Dawson method for two maneuvers at intersection A.

$t_{c,j}$	X	Y	Z	$t_{f,j}$	X	Y	Z
X	—	<1 s	<1 s	X	—	<1 s	<1 s
Y	<1 s	—	3.28 s	Y	<1 s	—	1.76 s
Z	6.62 s	4.46 s	—	Z	3.87 s	2.53 s	—

Table 4.
Observed $t_{c,j}$ and $t_{f,j}$ values for all maneuvers at intersection A.

Study intersection	Control delay ($d_{\text{entire intersection}}$)	Level of Service (LoS)	Total crash cost (TTC)
	s/veh		EUR
A	14	B—vehicle control delay 10–15 s	251,637
B	26	D—vehicle control delay 25–35 s	363,698
C	33	D—vehicle control delay 25–35 s	642,850
D	17	C—vehicle control delay 15–25 s	340,640

Table 5.
Overview of control delay and crash costs at non-circular intersections with the old configuration.

Exhibit 17-2 of the HCM2016 [13]. **Table 5** shows the d_j values for the intersections investigated as listed in **Tables 2** and **3** and the corresponding crash costs from the cost of an injured person approximately equals to 73,631 Euro, fatality equals to 1,394,434 Euro, and damaged vehicles almost of 7686 Euro.

Table 5 shows that the total crash cost (TCC) increases when the control delay of the entire intersection $d_{\text{entire intersection}}$ investigated increases: when the mean dj of the vehicles leaving the intersection area increases, this indicates that drivers do not feel safe to make the maneuver. This circumstance is mainly due to the poor geometric configuration of the intersection and, as confirmed by the preliminary results of this study, can amplify the frequency and severity of crashes.

Figure 7 shows a positive linear relationship using the ordinary least square method to predict the total crash cost in euros by varying the average control delay at the entire intersection, which is a measure of LoS (Eq. (9)). The parameters

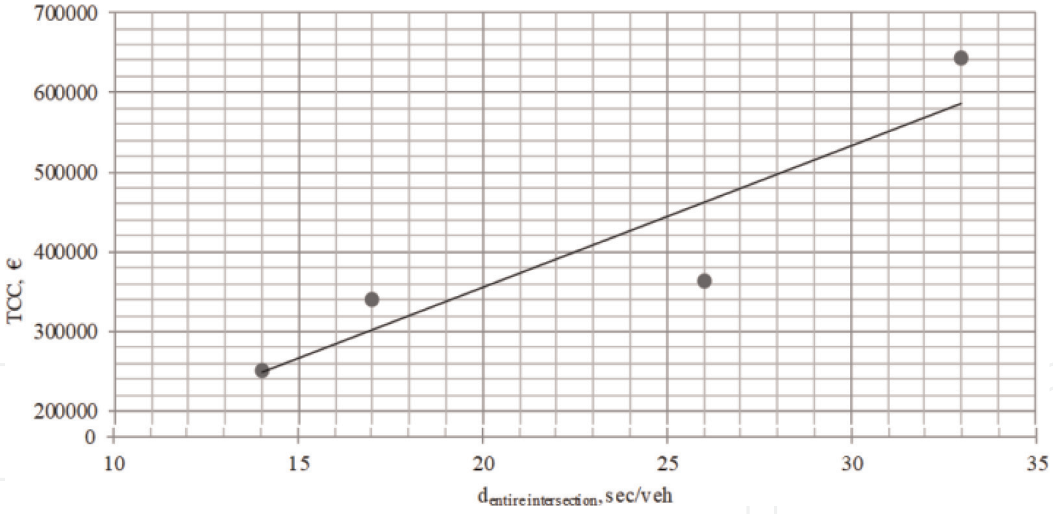


Figure 7.
Total crash cost versus average control delay of the entire intersection.

Std. error	t-value	p-value	Lower confidence limit	Upper confidence limit
1457.90	12.19	0.001189	13130.97	22410.36

Table 6.
Statistical parameters of the regression model.

included in the TCC prediction model are significant with a 95% level of confidence (**Table 6**). The adjusted coefficient of determination (R^2) of the model is 83%.

$$TCC = 17.771 d_{entire\ intersection} \tag{3}$$

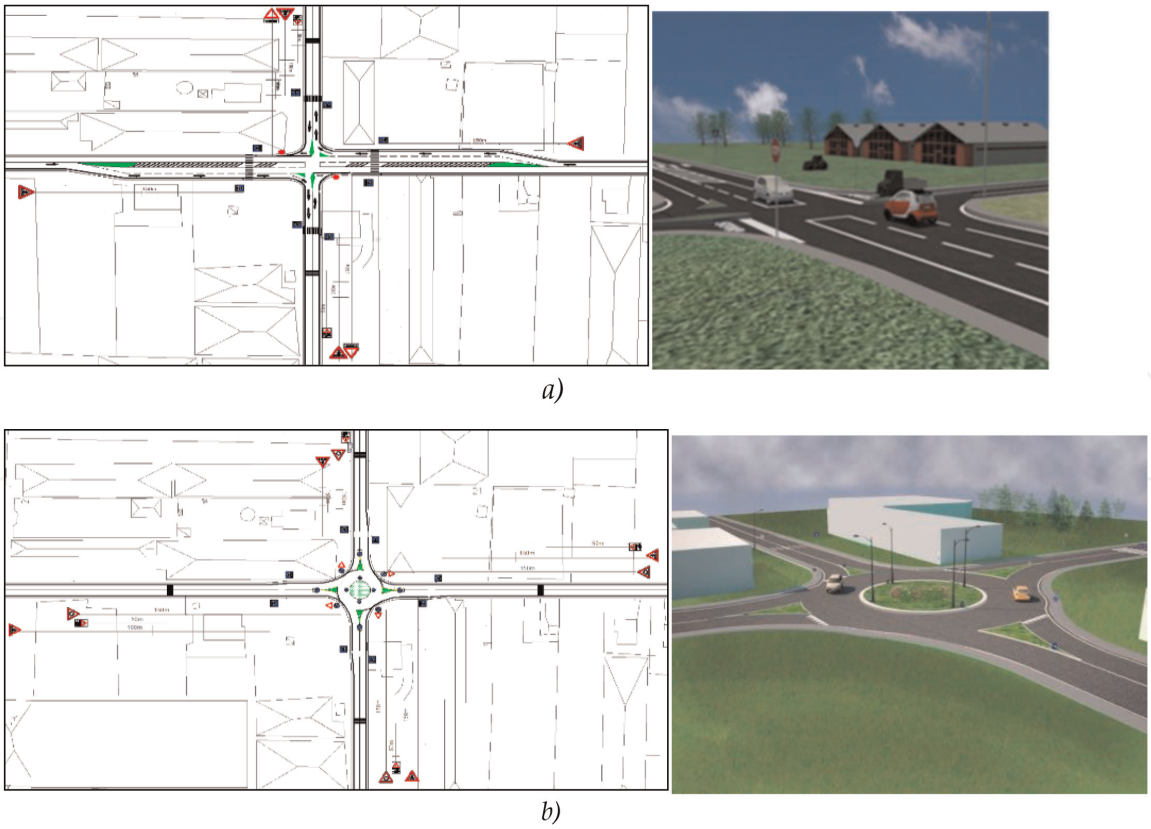
4.3 Treatment to manage and reduce the crash level by carrying out strategies able to improve the expected LoS and safety levels

The next step in the research was to design different geometric solutions (**Figure 8**) for intersection D (**Figure 5**), which has a high crash rate, medium-high crash cost, low-medium LoS (**Table 5**) and to estimate, on the one hand, the expected LoS and, conversely, the expected reduction of the annual crash frequency of the configurations hypothesized. The solution shown in **Figure 8a** is an adaptation of intersection D to the requirements of the Italian Road Design Standard on the geometric design of road intersections [14]. The solution shown in **Figure 8b** refers to transforming the shape into a compact roundabout.

4.3.1 Control delay: comparing before and after solutions

Before redesigning the geometric configuration of the area of intersection to include a roundabout, for which the investigated database showed that the mean crash rate over 5 years was lower than at non-circular intersections, it was decided to adjust the current non-circular intersection in line with the requirements of the Italian Standard in force in two phases:

a. **Phase I**: adjusting the radius of the edges of the entry and exit legs of the intersection, the width of the traffic lanes, the removal of obstacles in the areas within the so-called sight triangles, and the addition of median-refuge islands on the major and minor roads, as recommended by the Italian Road Design Standard [14];



a)

b)

Figure 8.
Advanced geometric design solutions for an existing non-circular intersection. (a) Adjustment according to the Italian Standard. (b) Changing the configuration into a compact roundabout (Dext = 26 m) according to the Italian Standard.

b. **Phase II**: adding left-turn lanes on major-road approaches based on the ratio between the volume of vehicles turning left per hour and the total traffic volume on the highway per hour.

Right-turn lanes on minor road stops are not permitted by the Italian Design Standard [14], and they are not included in the design.

The intersections investigated are almost totally equipped with right-turn lanes on major roads and they have lighting within and approaching the intersection area; consequently new lighting and new right-turn lanes on major roads are not required. Control delay at the entire intersection for the first advanced geometric solution of intersection D (**Figure 8a**) was estimated as in Section 3.2; the expected LoS of this geometric adjustment is shown in **Table 7**. In particular, to compute the

Non-treatment site		**Expected configurations**		
Control delay on the entire intersection, s/veh	**LoS before treatment**	**Site**	**Control delay on the entire site, s/veh**	**LoS after treatment**
17	C	Intersection*	9	A
		Compact roundabout**	4	A

*Adjusted to the Italian Standard without changing the shape by adding further modules **Figure 8a**.
***Figure 8b**.*

Table 7.
*Comparison of the control delays at advanced geometric solutions with those of intersection D (**Figure 4**, old configuration).*

average control delay for the roundabout approach as a whole in order to make comparisons with other intersection types, control delay d_j for the i^{th} approach was calculated by computing a weighted average of the delay for each lane on the approach (Eq. (7)), weighted by the volume in each lane. The calculation is shown in Eq. (10) using SETRA diagrams for the expected control delay at each maneuver, as the calibration conditions reflect the actual study context.

$$\mathrm{d}_{\text{approach, i}} = \frac{\mathrm{d}_{\text{left lane}} \times \mathrm{q}_{\text{left lane}} + \mathrm{d}_{\text{right lane}} \times \mathrm{q}_{\text{right lane}}}{\mathrm{q}_{\text{left lane}} + \mathrm{q}_{\text{right lane}}} \tag{4}$$

The control delay $d_{entire\ roundabout}$ for the entire roundabout is similarly calculated by computing a weighted average for the delay at each approach, weighted by the volume on each approach and represented by Eq. (11):

$$d_{entire\ \ roundabout} = \frac{\sum d_{approach,\, i}\ q_i}{\sum q_i} \tag{5}$$

where $d_{entire\ roundabout}$ is the control delay for the entire roundabout, s/veh; $d_{approach,k}$ is the control delay for approach k^{th}, s/veh; q_i is the flow rate for approach i^{th}, vph.

4.3.2 Control delay at the entire intersection: comparing before and after solutions

It is imperative for a designer to understand the relationships between design features and crash frequency.

The effectiveness of all the changes that have been designed without changing the shape of a regular intersection but adjusting it to the Italian Standard (see **Figure 8a** and Section 4.3.1) was confirmed by the expected crash frequency values computed by adopting the SPF available in Biancardo et al. [16]. Biancardo et al. [16] worked in line with HSM2010 [17] procedure and revised the equation available in the Manual to predict crash frequency at three and four-leg rural unsignalized at-grade intersections.

The N_{spf} formulation [16] was here used (see Eq. (12)) to predict the crash frequency at the two-lane two-way four-leg intersections studied in greater depth (intersection D) as it was calibrated using a data set that adequately reflects and partly overlaps with what is explored here. MLW is the mean lean width of the approaching and departing lanes.

$$N_{spf} = AADT \cdot\ \exp\left[-1.042 \cdot MLW - 8.5\right] \tag{6}$$

Eq. (12) applies to an AADT_{maj} range from 0 to 14,700 vpd and AADT_{min} range from 0 to 3500 vpd.

In HSM2010 [17], Crash Modification Factors (CMFs) are introduced to account for the specific site conditions that differ from the hypothesized base conditions. Under base conditions, the CMF is 1.00 (i.e., **Figure 5d**), while the CMF is less than 1.00 when a geometric configuration in compliance with the Standard and with many additional modules exists and, consequently, a reduction of average yearly crash frequencies can be expected. $\text{N}_{\text{predicted}}$ (predicted average crash frequency for a specific year for site type x) is shown in Eq. (13), where the effect of the skew angle does not appear, as study intersection D has an 80° angle, very close to orthogonal road axes and, consequently, no additional benefits can derive from further correction or the right-turn lanes that already exist on major roads.

$$N_{predicted} = N_{spf} \cdot CMF_{LTL} \cdot \tag{7}$$

where N_{spf} was determined by the following Eq. (12).

CMF_{LTL} was computed using the HSM procedure, and it benefits from the effects of the presence of left-turn lanes (LTL) on the major road, specifically in terms of expected average annual crash frequency reduction compared with what can be observed at intersections with a poor geometric configuration. CMF_{LTL} is equal to 1 for four-leg unsignalized rural intersections that meet base conditions. It equals 0.13 for the left-turn lanes present [16].

Table 8 shows, in the light of the foregoing, the expected annual number of crashes if the intersection is adjusted to Italian Road Design Standard [14] requirements by introducing additional geometric modules as listed in the first part of Section 3.3.1.

Moving on now to the evaluation of the effectiveness of the second treatment (the conversion of typical intersections into compact roundabouts) suggested for intersection D in order to check whether the level of exposure to crash risk can be reduced and is generally well managed, the EB procedure was adopted, as mentioned in the Literature review section.

First of all, it is necessary to calculate the expected annual number of crashes (m) if conversion to a roundabout does not take place. Eq. (14) was adopted to obtain a site-specific estimate of the m variable at a typical intersection before conversion to a roundabout:

$$m = w_1 x + w_2 P \tag{8}$$

where m is the expected site-specific annual number of crashes or injury crashes before conversion; x is the count of crashes in the n years before conversion (see **Table 2**, a total of 14 crashes occurred in 5 years with 4 injuries); n = 5 is the study period in this research; w_1 and w_2 are weights, Eqs. (15) and (16) [18]:

$$w_1 = \frac{P}{\frac{1}{k} + nP} \tag{9}$$

$$w_2 = \frac{\frac{1}{K}}{\frac{1}{k} + nP} \tag{10}$$

where P is the prediction of the annual number of crashes, or the annual number of injury crashes depending on what it is necessary to investigate using an SPF to identify intersections with similar characteristics before conversion; k is the dispersion parameter for a given model, estimated from the SPF calibration process using a maximum likelihood procedure.

Case study	**Crashes per year**	
Intersection D	**Total**	**Injury**
Expected annual number of crashes	1.99	0.57
Expected annual changes to the number of crashes	−0.81	−0.23
Reduction in crashes	−28%	−29%

Table 8.
Calculation of the expected change to the number of crashes after shape adjustment in line with the requirements of the Italian Road Design Standard.

Case study—Intersection D	Crashes per year	
	Total	**Injury**
BEFORE (neither adjustment nor conversion) (Eq. (14))		
P	0.89	0.20
K	0.77	1.25
w_1	0.15	0.11
w_2	0.23	0.45
m	2.37	0.64
AFTER (after conversion to roundabout—solution 2)		
Expected annual number of crashes	1.86	0.26
Expected changes in no. of crashes	−0.51	−0.38
Reduction in no. of crashes	−21%	−59%

Table 9.
Calculation of the expected change in the number of crashes when intersection D is converted into a roundabout.

Rodegerdts et al. [18] suggested k equals 0.77 for an SPF that predicts the total number of crashes per year, and k equals 1.25 for an SPF that predicts the total number of injury crashes per year. In chapter C, [18] are defined the results of the efforts to develop intersection and approach-level models. These models relate crash prediction to the number of lanes, number of legs, and the average annual daily traffic. SPFs used to predict the expected total number of crashes per year at intersection (Eq. (17)) or the expected total crash injuries per year at intersection (Eq. (18)) are as follows:

$$P = \exp(-8.63) \cdot \left(AADT_{\text{total entering}}\right)^{0.952} \tag{11}$$

$$P = \exp(-8.733) \cdot \left(AADT_{\text{total entering}}\right)^{0.795} \tag{12}$$

Eqs. (17) and (18) have been used in this study to predict m variable, since they were validated using the data set that is adopted here as shown in [16].

Eq. (19) was adopted to predict the expected total crash frequency per year after converting the intersection into a single-lane roundabout [19], where $\text{AADT}_{\text{total entering}}$ is the total annual average daily traffic entering the roundabout, equal to 7642 vpd for the intersection in question.

$$m = 0.023 \cdot \left(AADT_{\text{total entering}}\right)^{0.749} \tag{13}$$

The expected safety effects are shown in **Table 9**.

5. Results and discussions

A comparison of the expected crash frequency between conversion and non-conversion into a single-lane roundabout of the four-leg two-way-stop intersection is performed by plotting **Figure 9**. This makes it possible to identify a maximum threshold for the $AADT_{total\ \text{entering}}$ at the single-lane roundabout when this configuration replaces an existing typical intersection without damaging the required safety levels.

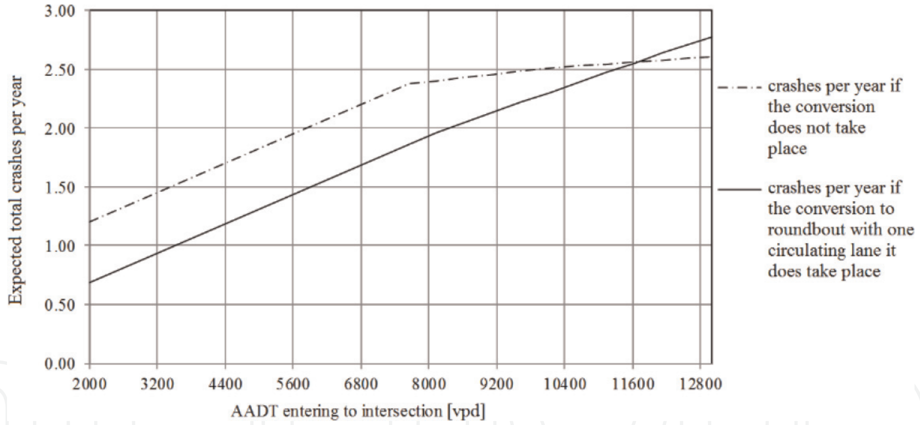


Figure 9.
Roundabout performance in terms of expected crash frequency for $AADT_{total\_entering}$.

The results summarized in **Table 10** and listed below highlight a strong correlation between the LoS and the safety level for managing hotspots along road networks and the corresponding crash risk levels, improving system quality for users. The results achieved show that, by increasing control delay throughout the entire intersection, the expected safety level for the expected annual number of crashes decreases. Conversely, when the estimated level of service increases (reducing the control delay of the entire intersection), the safety level improves (translating into a low value for the expected value of annual crashes per year). Results confirm that if a study intersection, under specific traffic conditions, and in a specific environmental and surrounding context, has a suitable and correct geometric configuration for reducing the number of conflict points during possible maneuvers, the control delay on the entire structure is reduced, and the LoS improves. This reflects indirectly, but positively, on the safety level because the expected value of the annual crashes decreases.

This research aimed to identify road strategies to improve road safety conditions at rural two-lane two-way intersections with stop-control in order to identify crash risk factors that may affect the Level of Service (LoS) and the safety level of the

Study case Intersection D	**Before**	**After**	
	No treatment site	**Solution No. 1**	**Solution No. 2**
		Conversion to compact roundabout	**Adjustment to the Italian Standard by designing additional geometric modules**
Expected control delay of the entire intersection	17 s/veh	4 s/veh	9 s/veh
Expected annual number of site-specific crashes	2.37	1.86	1.99
Level of Service (LoS)	C	A	A
Reduction in total crashes per year		21%	16%
Reduction in injury crashes per year		59%	31%
Annual economic benefit in crash savings		29,000 EUR	16,000 EUR

Table 10.
LoS and expected crash frequency at advanced geometric solutions.

road system on the one hand, and to analyze the effectiveness of treatment for the effective management of hotspots and ensure the good operation of the system, on the other hand. The procedure investigated can help in the allocation of resources according to the needs and severity of a possible crash event that, although rare, can have dramatic consequences, especially when risk factors are not identified, analyzed, and reduced.

6. Conclusions

In this chapter, a methodological process that can also be implemented in other domains was shown to calculate, manage, and reduce, through appropriate treatments, the expected crash risk level measured in terms of yearly crash frequency and Level of Service.

First of all, the procedure aimed to identify, and then manage, the hotspots on a rural road intersection network where high exposure to crash risk can be observed. It also sought to rank the hazardous sites, for which two measures of exposure to risk were suggested and assessed in line with the research presented, namely the crash rate and Level of Service in terms of control delay at the intersection area.

Of course, a safe system approach requires a fundamental cultural and ethical shift in thinking, but it is also true that the current road transport system is not as safe as it could be. However (a) if the system could be well supervised, (b) if the trend of a number of system status indicators (i.e., crash rate level, level of service, crash cost, etc.) could be carefully plotted to check their decay over time, (c) if design errors were promptly identified, and (d) if the correlations between design errors/access management and factors that cause increased exposure to crash risk were then investigated, in the event of human error or driver distraction, the resulting severity might not be as high. Obviously, system designers and system users must all share responsibility for managing crash forces to a level that does not result in death or serious injury.

It has been verified whether improvements can be achieved in terms of safety level (reduction of the number of crashes and injuries) and the quality of traffic (reduced control delay over the entire intersection) when the geometric design of existing intersections belonging to two-lane rural roads and located on a flat area does not meet the Italian Standard.

The experimental method covered two parallel trajectories that ultimately converge:

- adapting an existing at-grade intersection without changing its shape;
- changing its geometry according to the Italian standards, keeping traffic features and environmental conditions constant.

The results show that for the intersections in question, designing a single-lane roundabout according to the Italian Road Design Standard, or an intersection introducing left-turn lanes, deceleration lanes, and median-refuge islands could help to achieve this goal. Compact roundabouts are, in any case, the best solution in terms of Level of Service and safety level because they contribute to strongly reducing delay as well as crashes.

Conflict of interest

No potential conflict of interest was reported by the authors.

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