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RURAL TWO-LANE TWO-WAY THREE-LEG AND FOUR-LEG STOP-CONTROLLED INTERSECTIONS: PREDICTING ROAD SAFETY EFFECTS

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Abstract. The study focused on grade-level rural two-lane two-way three-leg and two-lane two-way four-leg stop-controlled intersections located in the flat area with a vertical grade of less than 5%. The goal is to calibrate one Safety Performance Function at these intersections by implementing a Generalized Estimating Equation with a binomial distribution and compare to the results with yearly expected crash frequencies by using models mainly refered to the scientific literature. The crash data involved 77 two-lane two-way intersections, of which 25 two-lane two-way three-leg intersections are without a left-turn lane (47 with left-turn lane), 5 two-lane two-way four-leg intersections without a left-turn lane (6 with a left-turn lane). No a right-turn lane is present on the major roads. Explanatory variables used in the Safety Performance Function are the presence or absence of a left-turn lane, mean lane width including approach lane and a left-turn lane width on the major road per travel direction, the number of legs, and the Total Annual Average Daily Traffic entering the intersection. The reliability of the Safety Performance Function was assessed using residuals analysis. A graphic outcome of the Safety Performance Function application has been plotted to easily assess a yearly expected crash frequency by varying the Average Annual Daily Traffic, the number of legs, and the presence or absence of a left-turn lane. The presence of a left-turn lane significantly reduces the yearly expected crash frequency values at intersections.

Keywords: comparisons, four-leg, grade-level intersections, safety performance function, three-leg, unsignalized, yearly crash frequency.

1. Introduction

Directive 2008/96/EC of the European Parliament and Council of 19th November 2008 on *Road Infrastructure Safety Management* identified the road infrastructures as the third pillar of road safety policy. This Directive makes a significant contribution to the *Crash Reduction Target of Community* by the European Parliament and the Council of the European Union Communication of 2nd June 2003, the *European Road Safety Action Programme, Halving the Number of Road Crash Victims in the European Union by 2010: a Shared Responsibility*.

An important aspect of improving highway safety lies in designing the geometric features of roadways in response to the characteristics and behaviour of drivers. Design criteria are being applied to specific features of highways with evidence of improvement in operation and safety (Leisch 1977).

Road intersections are critical elements of a road network because two or more roads join or cross one another and consequently the number of conflict points increases, causing a higher probability of road accidents.

The research presented here focuses on identifying road strategies to improve road safety conditions at rural two-lane two-way three-leg (3ST) and four-leg (4ST) stop-controlled intersections that cover most of the intersections on the studied road network.

The American Association of State Highway and Transportation Officials (AASHTO) in the Highway Safety Manual (HSM2010) by 2016 listed the objectives and strategies for improving safety at unsignalized intersections. Most of the objectives concern the physical improvement of unsignalized intersections and their approaches, while others relate to driver compliance. The strategies considered crossing the full range of engineering, enforcement,

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and education. The physical improvements considered include both geometric design modifications and changes to traffic control devices.

The main objective of the research is to make a contribution to bridging the gap existing in the literature where different Safety Performance Functions (SPFs) are used to calculate yearly expected crash frequency at 3ST and 4ST stop-controlled intersections. The yearly expected crash frequency was assessed by using equations included in the HSM2010 and in the National Cooperative Highway Research (NCHRP) Report 572 (Rodegerdts *et al.* 2007) and with one specific equation that belongs to the present research taking into account local conditions. The HSM2010 suggests the prediction of alternative *SPF*s as well as the correction of the HSM2010 *SPFs* available in the scientific literature so that they can properly reflect the real context and driver behaviour.

In this research study no crash associated with the physical conditions of the driver have been investigated; namely, crashes due to drowsiness, drunkenness, or distraction. Of course, crashes taking place at the intersection segments were not included in the study. By thoroughly analysing the crash reports that have been made available by the due authorities during the study period, only crashes owing to the risky manoeuvres of drivers were filtered and analysed to investigate the effects of road features on driver behaviour on undivided two-lane rural roads.

The research was carried out in steps as follows:

– investigating preliminary correlations between independent variables (geometric features and traffic measurement) and dependent variables (yearly observed crash frequency) by adopting statistical processing;
– removing anomalous yearly observed crash frequencies values using the 3σ method;
– calibrating an *SPF* able to predict yearly expected crash frequencies using Generalized Estimating Equation (GEE) method;
– carrying out a validation procedure on the *SPF* consisting in the evaluation of the residuals between predicted values by using calibrated *SPF* and observed values, and comparing results with available models of HSM2010 and Rodegerdts *et al.* (2007). The comparisons were made by calculating some main synthetic statistical parameters and plotting the diagrams of the cumulative squared residuals for each yearly expected crash frequency model by an increasing order of the Total Average Annual Daily Traffic ($AADT_{total}$) entering the intersection to check the absence of vertical jumps.

2. Literature review

According to Monga and Bishnoi (2015), the safety of a particular design assessed by studying the frequency with which types of crashes occur at certain particular types of the intersection and its correlation with traffic volume and vehicle composition. Designing safe intersections depends on many factors such as the Human Factor (decision and reaction time), Traffic Considerations (types of movements, crash experience), Road Environmental Considerations (geometric and safety features), and Economic Factors (cost of improvements in terms of safety).

Wang *et al.* (2002) developed an empirical approach to investigate a safety perception of drivers in specific road and traffic situations. This study identified the contribution of each attribute to the development of an Index of Perceived Safety (IPS), relating the perception of safety to attributes of a road and traffic situation.

Wang *et al.* (2013) provided a review of the factors with a specific focus on traffic and road related factors mainly for traffic accidents on the main roads. The factors affecting highway safety are numerous. In addition to traffic characteristics (driving speed, density, flow, and congestion) and road characteristics (road geometry and infrastructure), other factors also need to be examined and reviewed, such as the behaviour of road users, demographic factors, land use, and the environment.

Inappropriate or excessive speed has been identified as one of many variables that bring about crash-causing traffic conditions. After carrying out experimental studies in Spain, Matírnez *et al.* (2013) suggested perceptual countermeasures attract the attention of drivers to hazardous sites and force them to go slowly approaching the intersection. Recommended solutions were:

– painting transversal white lines at the beginning of the stretch;
– placing reflecting "cat eye" road studs in the verges;
– placing a "linear delineation system" in the safety barrier of the curve;
– placing reflecting barrier studs in the other barriers of the stretch;
– placing high-visibility panels along both traffic directions to mark the crossing.

Before and after analyses confirmed the effectiveness of the traffic speed measurements.

In the HSM2010 appropriate SPFs are used to predict average crash frequency for the selected year for specific base conditions. SPFs are regression models for estimating the predicted average crash frequency of intersections. The predictive method can be applied to existing sites, to design alternatives to existing sites, to design new sites, or for alternative traffic volume projections. An estimate can be made for the crash frequency of a prior period (what did, or would have, happened) or in the future (what is expected to happen).

Barua *et al.* (2010) examined the fatality risks of intersections located on rural undivided highways in Alberta, Canada. Offset intersections as well as intersections located on substandardized horizontal curves, sag curves, were associated with higher fatality risk. The results provided evidence regarding the need and importance of appropriate geometric design for intersections, particularly in rural locations.

Anowar *et al.* (2014) applied a partially constrained generalized ordered logit model to a sample of crash data from 1998 to 2006 to determine the factors contributing to the severity of intersection crashes in Bangladesh. In developing the statistical model, they selected variables from six broad categories: crash attributes, environmental factors, vehicle characteristics, roadway and operational features, intersection characteristics, and temporal indicators. In the research effort, they estimated three different models:

– ordered logit;
– generalized ordered logit;
– a partially constrained generalized ordered logit model.

Crash severity was found to increase in cases when the crash occurs on an undivided highway, involves a single vehicle, non-motorized vehicles, a motorized two-wheeler, a bus, truck or pedestrians. Severity also increases when the intersections are located in rural areas, and the crash occurs on dry pavement or during adverse weather. On the other hand, an intersection crash is likely to be less severe when traffic police attend the intersection. Based on these findings, they and Al-Ghamdi (2003) suggest that in addition to conducting a safety review and subsequent improvement of the existing intersection geometry, public education campaigns and law enforcement strategies are urgently needed to ameliorate the problems.

Candappa *et al.* (2015) design principles deemed relevant in aligning intersection design with Safe System approaches, including exploring the impact of speed and angle on the overall kinetic energy of a crash. The assessment provides broad conclusions on design factors that influence crash injuries such as possible impact speeds and angles and presents a platform for a more detailed evaluation system to be created. The assessment of designs is also an integral factor in maintaining a systems approach to improving intersection safety. Strategies to address intersection safety are diverse. Many strategies are engineering based, including geometric design and the application of traffic control devices (such as signs, markings, and signals). Most of the intersection safety work focuses on engineering – all share a common foundation in human factors. Quite often, a combination of these strategies needs solves a problem.

Establishing the human and vehicle thresholds beyond, which crashes at intersections are considered hazardous to health; creating a road environment, through intersection design, that supports these thresholds; and finally, evaluating driver response to these drawings, allow the various components of the system and their interplay to be recognized and strategically modified to achieve the end goal of a Safe System.

The study presented here belongs to a wider research program under way for several years now (Čokorilo *et al.* 2014; Dell'Acqua 2011, 2015; Russo *et al.* 2016) focused on the grade-level intersections. Those intersections belong to a two-lane rural road network in Southern Italy located on a flat terrain, built before the Italian Standard became law. According to *European Directive 2008/96/EC* on road safety, the analysis presented here was focused on the intersections with an observed crash. The *European Directive 2008/96/EC* indicates that the safety performance of existing roads should be raised by targeting investments for the road sections with the highest crash concentration and the maximum crash reduction potential. To be able to adapt their behaviour and increase compliance with traffic rules, in particular, specific speed limits, the *European Directive 2008/96/EC* specifies that drivers should be made aware of road sections with high crash concentrations.

3. Data collection

The crash data used in this research involved 77 unsignalized intersections, which belongs to two-lane rural roads in Southern Italy located in the flat area with a vertical grade of less than 5%. During the same study period, a total of 6 crashes were observed at 6 roundabouts.

Figure 1 shows an overview of the mean value of yearly observed crash frequency and yearly observed injury crash frequency for 3ST and 4ST intersections in the presence and absence of left-turn lanes and roundabouts by varying the number of legs.

The yearly (injury) crash frequency value for each intersection shows the number of (injury) crashes per year per 10^6 vehicles over an eight-year study.

The highest yearly observed crash frequency and yearly observed injury crash frequency values were observed at the 4ST intersections without a left-turn lane (0.240 and 0.222 respectively).

The values for yearly observed crash frequencies are lower at 3ST intersections without a left-turn lane than those observed at 4ST intersections without a left-turn lane.

A mean value of the yearly observed crash frequency of 0.181 for 3ST intersections without a left-turn lane (0.056 with a left-turn lane) and an average yearly injury crash frequency with a left-turn lane of 0.176 (0.060 with a left-turn lane) were observed. The average value of yearly observed crash frequencies for the roundabouts, with an observed value of 0.076 for a roundabout with four legs (injury crash frequency is 0.090) and 0.034 for a roundabout with three legs (injury crash frequency is 0.090) are less than those observed at 3ST and 4ST intersections. Roundabouts were not involved in the calibration phase of SPF due to small sample size.

The main features identified in the crash reports were as follows: the location of the intersection where the crashes happened, number of crashes, injuries and fatalities, crash type, type and number of vehicles involved, road surface conditions, lighting conditions, number of legs and lanes, the presence of left-turn lanes, lane width (approach lane width + left turn lane width on the major road), and divisional islands and deceleration lanes, as well as the diameter of the roundabouts, and $AADT_{total}$ entering the intersection.

A mean $AADT$ of 6400 vpd at 3ST and 4ST intersections ($AADT_{min}$ = 1000 vpd; $AADT_{max}$ = 20 000 vpd) and a mean

AADT of 8000 vpd at roundabouts ($AADT_{min}$ = 2000 vpd; $AADT_{max}$ = 20 000 vpd) were observed.

A total of 115 crashes were observed at intersections of which 83 resulted in injury crashes with a total of 124 injuries and 32 in property damage only. During the study period a total of 6 crashes were observed at roundabouts, 5 of which were injury crashes with a total of 7 injuries and one concerned property damage only.

Table 1 shows the main statistical average observed crash frequencies and average observed injury crash frequencies values with features by varying the intersection types from 2003 to 2010.

The coefficient of variation CV (the standard deviation divided by the mean value) is a dispersion index of the sample values around the mean and is independent of the unit of measure. The CV expresses the degree to which the standard deviation exceeds the average. In particular, if the CV is less than 0.5, the average is an unbiased estimator.

4. Overview of the procedures adopted as methodologies for predicting yearly expected crash frequency

4.1. Data analysis focusing on HSM2010 procedure for intersections located in rural areas

In Part C, the HSM2010 defines intersections as the junction of two or more roadway segments specifying that the intersection models estimate the mean value of the total yearly expected crash frequency that occur within the limits of an intersection and intersection-related crashes that occur on the intersection legs, which depends on the characteristics of the accident. In Part C of the HSM2010, models for the mean value of the total yearly expected crash frequency at particular rural two-lane two-way road are available. The effects of the major and minor road traffic volumes ($AADT_{maj}$ and $AADT_{min}$, respectively, in vpd) on yearly crash frequency is incorporated through SPFs, while the effects of geometric design and traffic control

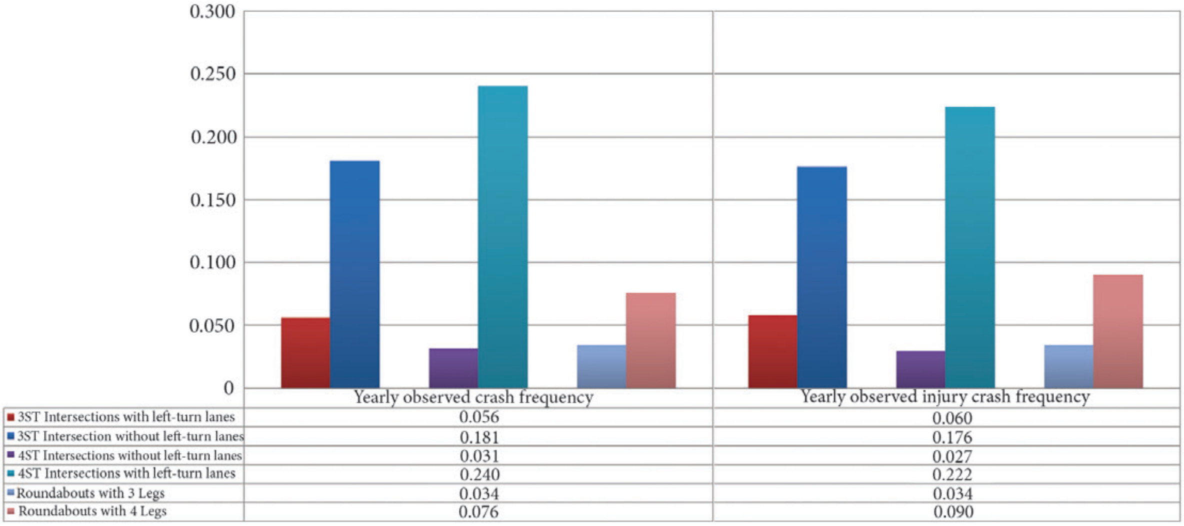

Fig. 1 Overview of the total and injurious yearly crash frequencies mean values for 3ST and 4ST intersections and roundabouts

Table 1. Overview of crashes frequencies and features analysed

Intersection Type	*AADT*, vpd	Mean lane width, m	Yearly observed crash frequency			Yearly observed injury crash frequency		
	Mean		% of intersection types over the total number	Mean	CV	% of intersection types over the total number	Mean	CV
3ST intersections without left-turn lanes	4100	4	28	0.181	0.374	26	0.176	0.401
3ST intersections with left-turn lanes	5000	4	53	0.056	0.384	33	0.060	0.332
4ST intersections without left-turn lanes	2100	4	6	0.031	0.153	2	0.027	0.000
4ST intersections with left-turn lanes	11 100	4	7	0.240	0.257	7	0.222	0.354
Roundabout with 3 Legs	10 000	4	1	0.034	0.000	1	0.034	0.000
Roundabout with 4 Legs	10 000	4	6	0.076	0.712	4	0.090	0.486

Note: Mean – average value; CV – coefficient of variation, which is equal to standard deviation divided by mean value.

features are incorporated through the Crash Modification Factors (CMF_s).

Equation (1) presents the general HSM2010 SPF for ST intersections:

$$N_{predicted,\text{int}} = N_{spf\,\text{int}} C_i \; CMF_{1i} CMF_{2i} ... CMF_{4i} \big), \quad (1)$$

where $N_{predicted,\text{int}}$ – the average expected crash frequency value for an individual intersection for the selected year; $N_{spf\,\text{int}}$ – the for average expected crash frequency value an intersection with base conditions; CMF_s – applied to account for the effects of site-specific geometric design and traffic control features; C_i – a model correction to account for site-specific characteristics such as the environment, user behaviour, driving laws, and enforcement level.

4.1.1. HSM2010 average expected crash frequency value in base conditions

The HSM2010 *SPF* for 3ST and 4ST intersections are shown in Eqs (2) and (3) respectively:

$$N_{spf\ 3ST} = \exp\Big[-9.86 + 0.79\ln\Big(AADT_{maj}\Big) + 0.49\ln\ AADT_{min}\big)\Big], \quad (2)$$

$$N_{spf\ 4ST} = \exp\Big[-8.56 + 0.60\ln\Big(AADT_{maj}\Big) + 0.61\ln\ AADT_{min}\big)\Big]. \quad (3)$$

Eq (2) is applicable to an $AADT_{maj}$ ranging from 0 vpd to 19 500 vpd and an $AADT_{min}$ ranging from 0 vpd to 4300 vpd; Eq (3) applies to an $AADT_{maj}$ ranging from 0 vpd to 14 700 vpd and $AADT_{min}$ ranging from 0 vpd to 3500 vpd. Application to sites with *AADT*s substantially outside these ranges may not provide reliable results.

4.1.2. HSM2010 Crash Modification Factor

The base conditions which apply to the SPFs in Eqs (2) and (3) require an intersection skew angle equal to 0 degrees, the absence of left-turn lanes and right-turn lanes on approaches without stop control, and no lighting.

For all the intersections that failed to meet the local base conditions, CMF_s for skew angle (CMF_{sa}), left-turn lanes (CMF_{lt}), right-turn lanes (CMF_{rt}), and lighting (CMF_{light}) are suggested. The CMF_s are the ratio (Eq (4)) of the mean value of the estimated average yearly crash frequencies for specific intersection under non-base conditions (Condition B) over the average value of the yearly expected crash frequencies for specific intersection base conditions (Condition A). Under base conditions, the *CMF* is 1.00. For each class that has been formed to reflect the yearly observed crash frequency properly, a CV has been calculated, to make consistent and reliable values for CMF_s by varying the geometric explanatory variables investigated.

$$CMF_i = \frac{\text{yearly crash frequency with Condition B}}{\text{yearly crash frequency with Condition A}}. \quad (4)$$

4.1.2.1. Skew angle HSM2010 Crash Modification Factor

The base condition for the intersection skew angle is 0 degrees of skew (an intersection angle of 90 degrees). The skew angle of an intersection was defined as the absolute value of the deviation from an intersection angle of 90 degrees. The absolute value is used in the definition of the skew angle because positive and negative skew angles are considered to have similar detrimental effects.

The *CMF* for an intersection angle with stop-control on the minor approach is:

$$\text{3ST intersections: } CMF_{sa} = \exp^{\,0.004SKEW\big)}, \quad (5)$$

$$\text{4ST intersections: } CMF_{sa} = \exp^{\big(0.0054SKEW\big)}, \quad (6)$$

where *SKEW* – the intersection skew angle (in degrees), the absolute value of the difference between 90 degrees and the actual intersection angle. This *CMF* applies to total intersection crashes.

4.1.2.2. Number of approaches with left-turn lanes HSM2010 Crash Modification Factor

The base condition for intersection left-turn lanes is the absence of left-turn lanes on the intersection approaches. Table 2 presents the *CMFs* for the presence of left-turn lanes. These *CMFs* apply to the installation of left-turn lanes on any approach to a signalized intersection, but only on uncontrolled major road approaches to a stop-controlled intersection. The *CMFs* for installation of left-turn lanes on multiple approaches to an intersection are equal to the corresponding *CMF* for the installation of a left-turn lane on one approach raised to a power equal to the number of approaches with left-turn lanes.

4.1.2.3. Number of approaches with right-turn lanes HSM2010 Crash Modification Factor

The base condition for intersection right-turn lanes is the absence of right-turn lanes on the intersection approaches. These CMF_s apply to the installation of right-turn

Table 2. Crash Modification Factor for installation of left-turn lanes on intersection approaches (Exhibit 11-32 in HSM2010)

Intersection type	Intersection traffic control	Number of approaches with left-turn lanes	
		one approach	two approaches
3ST intersection	Minor road stop control	0.56	0.31
4ST intersection	Minor road stop control	0.72	0.52
	Traffic signal	0.82	0.67

lanes on any approach to a signalized intersection, but only on uncontrolled major road approaches to stop-controlled intersections. The CMF_s for the installation of right-turn lanes on multiple approaches to an intersection are equal to the corresponding *CMF* for installation of a right-turn lane on one approach raised to a power equal to the number of approaches with right-turn lanes. The CMF_s in Table 3 apply to total intersection crashes. A *CMF* value of 1.00 is always used when no right-turn lanes are present.

4.1.2.4. Lighting HSM2010 Crash Modification Factor

The base condition for lighting is the absence of intersection lighting. The *CMF* for lighted intersections is calculated as:

$$CMF_{light} = 1 - 0.38 p_{ni}, \quad (7)$$

where p_{ni} – proportion of total crashes for unlighted intersections that occur at night. This *CMF* applies to the total number of crashes observed at intersection. Table 4 presents default values for the night-time crash proportion p_{ni}.

The predictive models in Eqs (2) and (3) are calibrated to local State or geographic conditions.

4.1.3. HSM2010 calibration factor for intersections

The calibration factor for intersections of a specific type developed for use in a particular jurisdiction or geographical area. The value of C_i is based on the ratio of the total intersection crashes.

yearly observed crash frequencies for a selected set of sites to the total average predicted yearly crash frequency estimated for the same sites during the same period using the applicable Part C of HSM2010 (Eq (8)).

Table 3. Crash Modification Factor for installation of right-turn lanes on intersection approaches (Exhibit 11-33 in HSM2010)

Intersection type	Intersection traffic control	Number of approaches with right-turn lanes	
		one approach	two approaches
3ST intersection	Minor road stop control	0.86	0.74
4ST intersection	Minor road stop control	0.86	0.74
	Traffic signal	0.96	0.92

Table 4. Night-time crash proportions for unlighted intersections (Exhibit 11-34 in HSM2010)

Intersection type	Proportion of crashes that occur at night
	p_{ni}
3ST	0.260
4ST	0.244

$$C_i = \frac{\sum_{all\ iST\ intersection} observed\ crashes}{\sum_{all\ iST\ intersection} predicted\ crashes}. \quad (8)$$

Thus, the nominal value of the calibration factor, when the observed and predicted yearly crash frequencies happen to be equal, is 1.00. When there are more crashes observed than are predicted by the HSM2010 Part C predictive method, the computed calibration factor will be more than 1.00. When there are fewer crashes observed than are predicted by the HSM2010 Part C predictive method, the computed calibration factor will be less than 1.00. The default value of HSM2010 C_i is 1.50.

4.2. Data analysis focusing on NCHRP Report 572 procedure for intersections located in rural areas

In Chapter C, the NCHRP Report 572 (Rodegerdts *et al.* 2007) defines the results of the efforts to develop intersection-level and approach-level models. Major safety findings include intersection-level crash prediction models for the prediction of the overall safety performance of the intersection. These models relate the yearly expected crash frequency to the number of lanes, number of legs, and the *AADT*.

The SPFs used in the NCHRP Report 572 (Rodegerdts *et al.* 2007) to predict the crash frequency are as follows:

3ST intersections:

$$crash/year = \exp(-2.22)\left(AADT\right)^{0.254}, \quad (9)$$

4ST intersections:

$$crash/year = \exp(-8.63)\left(AADT\right)^{0.952}. \quad (10)$$

5. Data Analysis

Due to the low number of crashes observed at roundabouts, the SPF was calibrated only for unsignalized intersections. A preliminary analysis was conducted to identify the relationships between the possible explanatory variables using a Pearson correlation coefficient and the dependent variable considered for the yearly crash frequency prediction model. The variables used in the calibration phase are: number of legs (*NL*), mean lane width (*MLW*), *AADT* entering the intersection, and presence or absence of a left-turn lane (*LTL*) on the major road. No right-turn lanes exist on the major road of the intersections investigated, and only left-turn lanes on one approach to an intersection were observed.

5.1. Calibration local Safety Performance Factor

The Crash Modification Factor of presence or absence of a left-turn lane (CMF_{LTL}) was assessed by the HSM2010 procedure (Eq (4)). CMF_{LTL} is equal to 1.00 for 3ST and 4ST intersections that meet base conditions (absence of left-turn lanes). All 3ST and 4ST intersections, with left-turn lanes, were modified by the *CMF* value calculated using Eq (4) as presented in Table 5. Only left-turn lanes on one approach to an intersection were considered reflecting data investigated. Table 5 presents a mean value of the crash frequency per year by changing intersection type reflecting base (f_b) and non-base conditions (f_{nb}).

Considering the small sample size of the roundabout dataset analysed and that in the same *AADT* and geometrical conditions, the yearly observed crash frequency values at the roundabout are less than those observed at intersections, a GEE with a binominal distribution and an additional log linkage equation was adopted to calibrate the *SPF* in order to predict the yearly expected crash frequency only for the intersections. Table 6 presents the *SPF* and the goodness-of-fit measures for the GEE model. The *SPF* is good from statistical significance taking into consideration the Akaike Information Criterion (AIC) parameter and Pearson index of dispersion values.

Table 6 presents the reliability of the yearly expected crash frequency model checked in residual analysis on the same dataset in two steps.

First step: the mean residual of D_i difference between yearly observed and predicted crash frequencies was assessed and is equal to 0.074. A mean residual equal or near to zero allows the assumption that an accurate model was calibrated.

Second step: the standard deviation (σ) and mean (μ) of the sample values of differences between yearly observed and predicted crash frequencies were analysed using the 3σ method. The distribution of residuals confirms that the percentages of yearly crash frequency distribution came within the action limits (μ ± 3σ) and attention limits (μ ± 2σ). More than 70% of the residuals fall within the range μ ± σ, while more than 85% are within the attention limits. Residual analysis is an essential tool in this process since it makes it possible to identify where the predictive models may miss the mark, overestimating or underestimating the yearly observed crash frequencies.

5.2. Validation phase

The crash frequency predictive model suggested by the authors was compared to others available in the scientific literature, in particular:

a) the predictive model for 3ST and 4ST intersections presented in the HSM2010 (focusing on HSM2010 procedure for intersections located in rural area section);

b) the *SPFs* used in the empirical Bayes before and after analysis in the NCHRP Report 572 (Rodegerdts *et al.* 2007) (focusing on NCHRP report procedure for intersections located in rural area section).

The comparison of the yearly expected crash frequency using the models presented in Table 7 with the yearly observed crash frequency was checked in the residual analysis.

Three cases were identified for the residuals analysis:

- Case A: comparing yearly observed crash frequency for 3ST and 4ST intersections located in Southern Italy with yearly expected crash frequency using Eq (11) recommended by the authors.

Table 5. Values of the Crash Modification Factor of presence or absence of a left-turn lane

Intersection type	CMF_{LTL} for intersections in	
	base conditions	non-base conditions
3ST	1.00	f_b = 0.181 f_{nb} = 0.056 CMF_{LTL} = 0.31 CMF_{LTL} = 0.56 (for HSM2010)
4ST	1.00	f_b = 0.240 f_{nb} = 0.031 CMF_{LTL} = 0.13 CMF_{LTL} = 0.72 (for HSM2010)

Table 6. Goodness-of-fit measures for the Safety Performance Function

Equation		Log likelihood	Akaike Information Criterion (AIC)	Bayesian Information Criterion (BIC)	Pearson index of dispersion
$SPF = AADT\ CMF_{LTL} \exp\left(-1.0422MLW - 8.5\right)$	(11)	−16.86	0.45	−356.15	0.10

Table 7. Crash Frequency Prediction model comparison

Authors	Equation	
	$SPF = AADT\ CMF_{LTL} \exp\left(-1.0422MLW - 8.5\right)$	(11)
HSM2010 (2000)	$N_{spf\ 3ST} = \exp\left[-9.86 + 0.79\ln\left(AADT_{maj}\right) + 0.49\ln\left(AADT_{min}\right)\right]$	(2)
	$N_{spf\ 4ST} = \exp\left[-8.56 + 0.60\ln\left(AADT_{maj}\right) + 0.61\ln\left(AADT_{min}\right)\right]$	(3)
NCHRP Report 572 (Rodegerdts *et al.* 2007)	3ST intersections: $crash/year = \exp(-2.22)\left(AADT\right)^{0.254}$	(9)
	4ST intersections: $crash/year = \exp(-8.63)\left(AADT\right)^{0.952}$	(10)

– Case B: comparing yearly observed crash frequency for 3ST and 4ST intersections located in Southern Italy with yearly expected crash frequency using HSM2010 (Eqs (2) and (3)).
– Case C: comparing yearly observed crash frequency for 3ST and 4ST intersections located in Southern Italy with yearly expected crash frequency using NCHRP Report 572 (Rodegerdts *et al.* 2007) (Eqs (9) and (10)).

Table 8. Descriptive statistics of the residual analysis procedure results

Case investigated	Mean residual of D_i differences	Mean absolute deviation (MAD)	Mean squared error (MSE)
A	0.014	0.0004	0.0061
B	2.353	0.0654	0.2550
C	0.598	0.0016	0.1575

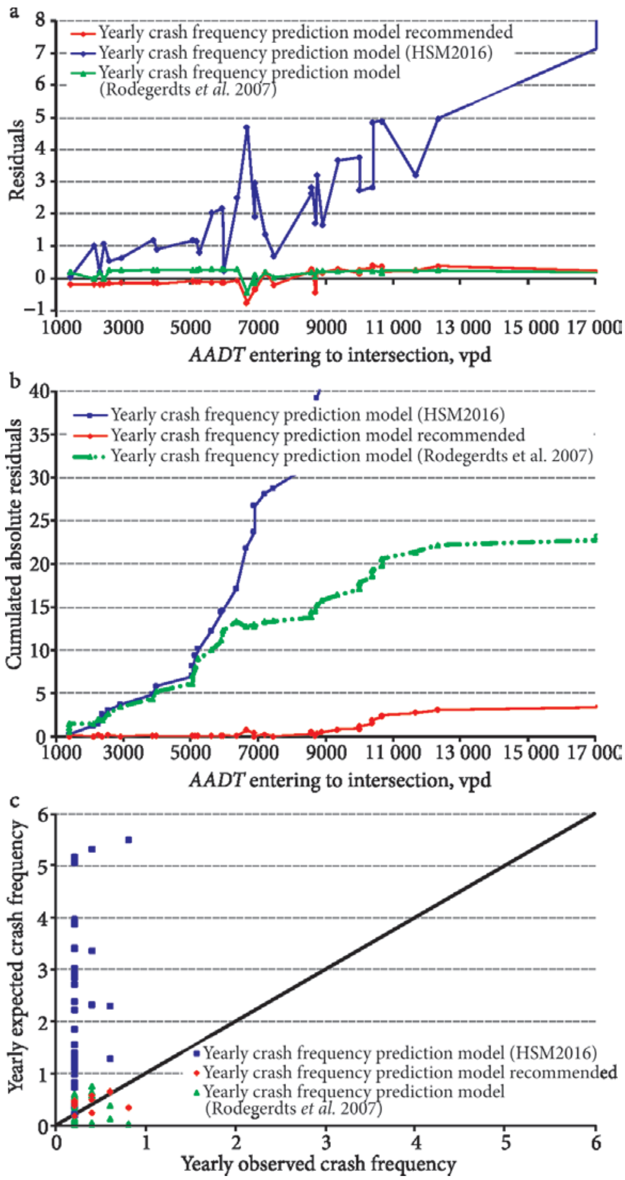

Fig. 2. Residual analysis and performance charts for the SPFs: a – residuals diagram cumulated; b – absolute residuals diagram; c – performance diagram

The residual analysis for the above three cases was carried out as follows:
– an assessment of the mean residual of D_i differences between yearly observed and predicted crash frequencies at each intersection;
– an assessment of the mean absolute deviation (MAD), i.e. the sum of the absolute values D_i divided by the number of intersections;
– an assessment of the mean squared error (MSE), i.e. the sum of D_{2i} values divided by the number of intersections;
– a diagram of the residuals and cumulated absolute residuals plotted by the $AADT_{total}$ entering the intersection (Figs 2a and 2b);

diagram of performance (Fig. 2c) where the *x*-axis shows the yearly observed crash frequency and the y-axis shows the yearly expected crash frequency.

Table 8 presents the reliability of the regression equations predicting yearly observed crash frequency. The results confirm the less value obtained for the MAD (0.0004) and the MSE (0.0061) indicators for local SPF recommended by the authors compared to other models widely used in the scientific literature.

A diagram of the residuals (Fig. 2a) was plotted, and it allows to recognize regions where the predictive models overestimate or underestimate the yearly observed crash frequency. It was observed a homogeneous distribution of the residuals for the *SPF* calibrated in this paper around zero instead of what it can be checked for the other available equations investigated. NCHRP models (Rodegerdts *et al.* 2007) return values closer to yearly expected crash frequency by using alternative local *SPF* calibrated than HSM2010 *SPF*. A cumulated absolute residual (Fig. 2b) was plotted by an *AADT* to check the absence of vertical jumps (more correctly known as outliers). A vertical jump would reflect the lack of flexibility in the functional form in the model and, in some cases, the existence of redundant data for a given value of the explanatory variable. Figure 2b proves the absence of jumps in the diagram of cumulated absolute residuals for the local *SPF* confirming the reliability of the yearly crash frequency prediction model recommended by the authors. A chart of performance (Fig. 2b) was plotted where the *x*-axis shows the yearly observed crash frequency for the 3ST and 4ST-intersections and the *y*-axis shows the yearly expected crash frequency using equations presented in Table 7. The diagram shows an overestimation of the predicted values than those observed by using HSM2010 *SPF* instead of what can be observed by applying local *SPF* calibrated. More generally NCHRP (Rodegerdts *et al.* 2007) equations fit better observed data than the first one; however local *SPF* is the best solution for predicting yearly expected crash frequency at study 3ST and 4ST intersections on rural area.

The results suggest less reliability for the HSM2010 model when applied to predict yearly expected crash frequencies for intersections on Italian roads. The model predicted by the authors preserves the original HSM2010 form and the relationship between independent variables and crashes. The results obtained for Italy suggest that the implementation of the HSM2010 techniques in road safety is oriented towards the development of local *SPFs* for a context as varied as the network analysed.

6. Results

An *SPF* that predicts yearly expected crash frequency at 3ST and 4ST intersections was performed by implementing the GEE method with binomial distribution using the *AIC*. *AADT*, number of legs, mean lane width, and CMF_{LTL} were adopted as explanatory variables to predict the model.

Residual analysis attested the reliability of the local *SPF*, compared to others models used in HSM2010 and by Rodegerdts *et al.* (2007) that overestimate yearly observed crash frequency in most of the cases.

The effects on crashes resulting from providing geometrical treatments are summarized by the HSM2010 (Table 9) where the addition of these extra modules reduces the *CMF* factor involved in predicting the total yearly expected crash frequency.

By the geometric treatments suggested by the HSM2010 to improve the ST intersections road safety conditions presented in Table 9, the *SPF* for intersections was implemented in an abacus (Fig. 3) showing the effects regarding yearly expected crash frequency reduction changing the value of the explanatory variables that refer to Table 9.

The diagrams show in Fig. 3, present yearly expected crash frequency on the *y*-axis, while the *x*-axis shows the exposure variable of the predictive model (Eq (11)), the *AADT* entering the intersection. Figure 3 presents a series of curves with a constant value for the remaining independent variables of the model in appropriate combination. The number of possible profiles for the *SPF* is equal to the number of available variables employed in the model on which it can work to improve road safety conditions. The

Table 9. Comparing some HSM2010 geometric treatments

Treatment	Setting (Intersection type)	*AADT*, vpd	Crash type (severity)	Crash Modification Factor	Standard Error
Potential crash effects of providing a left-turn lane on two approaches to 4ST intersections (Exhibit 14-20 in HSM2010)					
Provide a left-turn lane on both major-road approaches	Rural (4ST)	Major road from 1500 to 32400 Minor road ftom 50 to 11800	All types (all severities)	0.52	0.04
			All types (injury)	0.52	0.04
			All types (injury)	0.52	0.07
Potential crash effects of increasing intersection median width (Exhibit 14-26 in HSM2010)					
Provide a left-turn lane on both major-road approaches	Rural (4ST)	Unspecified	Multiple-vehicle (all severities)	0.96	0.02
			Multiple-vehicle (injury)	0.96	0.02
	Urban and suburban (3ST)		Multiple-vehicle (all severities)	1.03	0.01

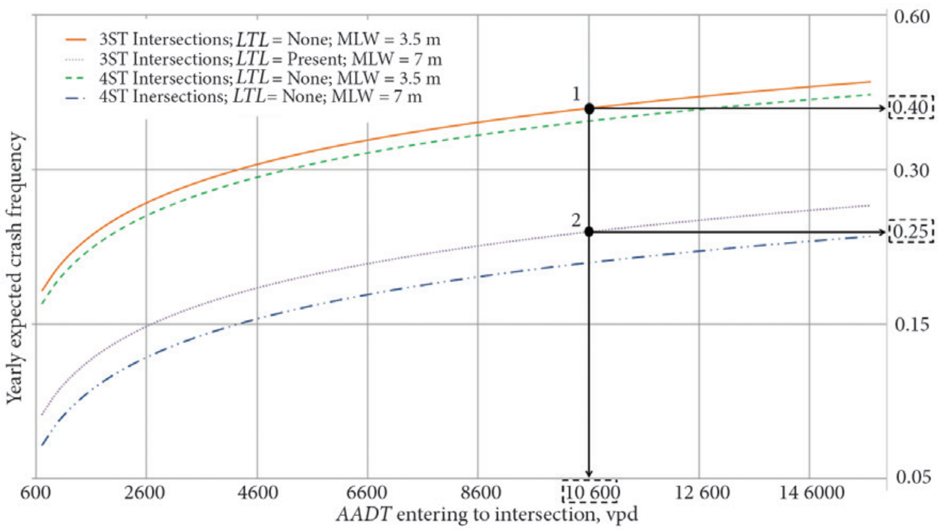

Fig. 3. Abacus-type for predicting yearly expected crash frequency for no circular intersections

results show that intersections provided with left-turn lanes are always characterized by a low-level of crash frequency compared to non-circular intersections. For example, concerning the line for 3ST intersections without left-turn lanes and the mean lane width equal to 3.5 m, a value of yearly expected crash frequency equal to 0.40 was observed in correspondence of an *AADT* entering the intersection value equal to 10 600 vpd entering the intersection. Moving from Point 1 to Point 2 where the *AADT* is kept while there is the presence of left-turn lanes and the mean lane width equal to 7 m, the yearly expected crash frequency for 3ST intersections reduces from 0.40 to 0.25.

The results should be used to conduct economic appraisals of improvements, prioritize projects, and evaluate the reduction in the number of crashes benefits of the treatments implemented. These applications can be used are used to consider projects and activities related not only to safety but also those intended to improve other aspects of the roadway, such as capacity and the transit service.

Future developments include potential crash effects by changing the geometric design of intersections, such as providing a right-turn lane on two approaches, providing a raised median or refuge island, and non-geometric design treatments such as stop ahead pavement markings, intersection illumination.

7. Conclusions

A Safety Performance Function to predict yearly expected crash frequency was performed by implementing the Generalized Estimating Equation method with a negative binomial distribution and the Akaike Information Criterion at two-lane two-way three-leg and two-lane two-way four-leg intersections. Mean lane width, average daily annual traffic, Crash Modification Factor of presence or absence of a left-turn lane (number of legs and presence or absence of a left-turn lane) factors were applied in the model. Residual analysis confirmed the reliability of the calibrated Safety Performance Factor, compared to others models widely used in the scientific literature (HSM2010, Rodegerdts *et al.* 2007) that overestimate yearly observed crash frequency in most of the cases. The Safety Performance Function for intersections was implemented in an abacus showing the effects regarding yearly expected crash frequency reduction changing the value of the explanatory variables. Intersections provided with left-turn lanes are always characterized by a low-level of crash frequency compared to non-circular intersections.

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