



## The influence of shoulder characteristics on the safety level of two-lane roads: A case-study



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### ABSTRACT

Constructing proper shoulders may improve road safety on two-lane roads. Previous research reported crash reductions following shoulder widening. This study aimed to examine the relationship between shoulder characteristics and crash occurrences on two-lane rural roads in Israel. The study database combined information on crash numbers, traffic volumes and road infrastructure characteristics of 3594 road sections. To examine a relationship between shoulder characteristics and crashes, given other road characteristics, two types of statistical models were developed: case-control and negative-binomial regression models, for several crash types. We found that the impacts of shoulder width and other road characteristics on crashes were generally consistent across various models and crash types, where a non-monotonous link between the shoulder width and crashes was typically observed. For various crash types, the models showed an increase in crash risk with an initial extension of the total shoulder, up to 2.2 m, and a consequent decrease in crashes with a further shoulder widening, over 2.2 m, by 2–6% and 1–4%, respectively, for each 0.1 m of shoulder extension. An increase in the width of unpaved shoulders, over 0.9 m, was associated with increased crash risk, in injury and total crashes, by 5% for each 0.1 m of shoulder extension. Lowest crash risks were found for total shoulder widths of about 3 m or more, but also for narrow total shoulders, below 1 m. Conversely, medium total shoulders, of 1.8–2.4 m in width, and unpaved shoulders of over 1 m, were associated with an increase in crash risk and, hence, are not recommended for use. The tools developed in the study may assist in decision-making during the design stages of a new road or upgrading existing road sections, on two-lane local roads.

### 1. Introduction

In Israel and in other countries, two-lane roads are characterized by a lower safety level compared to other road types, on the non-urban road network (Fitzpatrick et al., 2004; Mallschutzke et al., 2006; Gitelman and Korchatov, 2016). One of the measures for improving road safety on two-lane roads is building shoulders fitted to road and traffic conditions. The shoulder functions include provision for vehicle stops in emergency cases (without encroaching the travel lanes), providing a recovery zone for an errant vehicle, keeping space for road maintenance purposes, protecting the structural integrity of the pavement and others (Hauer, 2000; MOT, 2012). Studies conducted in the USA usually reported a decrease in road crashes following shoulder widening (Zegeer et al., 1980, 1981, 1988; Zegeer and Council, 1995; Miaou, 1996; Vogt and Bared, 1998; Council and Stewart, 1999; Harwood et al., 2000; Stamatiadis et al., 2009), in a monotonous form,

which was consequently adopted by summary estimates (IHSDM, 2004; AASHTO, 2010). Similarly, a positive relation was generally found between sealing (paving) shoulders and the level of road safety, where roads with paved shoulders are associated with fewer crashes than similar roads with unpaved shoulders (Hauer, 2000; World Road Association, 2003).

It is indicated (Hauer, 2000) that paved shoulders provide better protection for the road structure from being weakened by water or by erosion, and enable better controllability for stray or overtaking vehicles. Concerning the effect of shoulder width, as explained by Hauer (2000), wider shoulders provide a better recovery zone for erroneous or stray vehicles enabling them to avoid collisions with other vehicles and regain control that should enhance safety. On the other hand, there are concerns that wide shoulders may stimulate higher travel speeds or vehicle stops on shoulders that may be detrimental to safety.

Hauer (2000) conducted a detailed examination of the results of

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previous studies that evaluated impacts of shoulder characteristics on crashes and summarized that factual evidence was plentiful but diverse and not always consistent. It is suggested (Hauer, 2000; Stamatiadis et al., 2009) that safety effects of shoulder characteristics may change depending on traffic volume, lane width, road curvature and roadside conditions and, thus, should be estimated while controlling for other road and traffic characteristics.

In Israel, the interest in the relation between the shoulder width and road safety level has arisen recently, due to a revision of the road design guidelines (MOT, 2012). The local professional community believes in the importance of sealed shoulders for road's functioning and safety. Some local studies, e.g. Polus et al. (2005); Hakkert and Shokir-Hadad (2009), showed a dependence between worse infrastructure characteristics and higher crash rates on two-lane roads in Israel. However, the impact of shoulder characteristics on road crashes, particularly when controlling for other road features, was not explicitly examined in the past. Two-lane roads comprise over seventy percent of the length of the non-urban road network in the country (Gitelman and Korchatov, 2016). The purpose of this study was to examine the relationship between shoulder width and type, and crash occurrences on two-lane rural roads in Israel.

## 2. Existing knowledge on the impact of shoulder width

For freeways and divided roads, a reduction in crash occurrences was consistently found for wider right and/or left shoulders, when road infrastructure characteristics were used for predicting crashes (Xu et al., 2013; Venkataraman et al., 2013; Jung et al., 2014; Yu and Abdel-Aty, 2014; Serhiyenko et al., 2016). However, for two-lane roads the research findings are more diverse. Earlier studies typically reported final estimates of a decrease in crashes following shoulder widening. For example, Zegeer et al. (1988) developed multivariable statistical models using data from seven states and found that increasing the width of a paved shoulder by 1 feet reduces crashes by 6%, and paving 1 feet of a shoulder reduces crashes by 2%. Miaou (1996) modeled the relationship between single-vehicle crashes and road and traffic traits of two-lane sections in three states and estimated that increasing shoulder width by 1 feet reduces run-off-the road crashes by 8.8%. Council and Stewart (1999) developed models to predict crashes for two-lane roads in four states; the regression parameters of the models indicated a crash reduction by 12%–36% for 1 m extension of shoulder width. The summary values for two-lane roads in the USA (IHSDM, 2004; AASHTO, 2010) suggest, for example, for roads with over 2000 vehicles per day: a crash reduction of 13% for shoulder of 8 feet or wider, and a crash increase of 15%, 30% and 50% for shoulder widths of 4, 2 and zero feet, respectively, related to the basic value of 6 feet.

However, a detailed look at the data and findings of previous research of two-lane roads reveals that a reported decline in crash rate following an increase in shoulder width was not necessarily monotonous on the whole range of shoulder widths and for various crash types. For example, Zegeer et al. (1980, 1981) used a large database for two-lane roads in Kentucky. In that study, depending on various lane widths, the data showed an increase or no change in total crash rates within an initial change of shoulder width from zero to 5-ft, a consequent decrease in crash rates for 5 to 8-ft shoulders and various trends for wider shoulders, from 8 to 11-ft. In opposite-direction and run-off-road crashes, generally, a decrease was observed following an increase in shoulder widths, while other crashes increased.

Prinsloo and Goudanas (2003) analyzed ten-year crash rates of single-carriageway road sections in New South Wales, Australia, and reported that in some cases with similar characteristics of roadway width, number of lanes and lane width, an increase in shoulder width over 1.5 m was associated with higher crash rates related to narrower shoulders. Qin et al. (2004) fitted explanatory models for several crash types on two-lane roads using a database for over 29,000 km of roads in the USA, with their traffic and road characteristics. Having controlled

for other variables, the models indicated a negative relation between the shoulder width and multi-vehicle crashes (i.e., crash reductions for wider shoulders) but a positive relation between the shoulder width and single-vehicle crashes (i.e., crash increase).

Gross and Donnell (2011) developed explanatory models for total crashes on two-lane roads in Pennsylvania, using their traffic and road characteristics, by means of case-control and cross-sectional analyses. By both methods, positive values were found for the impacts on crashes of shoulder width categories from zero to 7 feet (i.e., an increase in crashes), with some fluctuation of values for various shoulder widths, while negative values and tangible crash reductions were received for the shoulder width categories of 8 to 10 feet.

Buddhavarapu et al. (2013) conducted crash-level injury severity modelling for crash occurrences on two-lane horizontal curves in Texas. Crash site features such as surface conditions, shoulder width, rural location, presence of a downward grade and lighting conditions were statistically significant in the estimation results. The elasticity analysis indicated that wider shoulders were associated with a decrease in non-injury crashes but with an increase in the probability of a fatal crash. A possible reason suggested for this result was the illusion of extra safety while driving on a roadway with wide shoulders.

Hosseinpour et al. (2014) developed prediction models for the number and severity of head-on crashes on federal roads in Malaysia; the majority of them were undivided two-lane roads. In the model for crash frequency, both paved and unpaved shoulder width had a negative impact on crashes indicating that shoulder widening by 1 m was associated with a 23% of crash reduction. At the same time, in the model for crash severity, the variable of paved shoulder width was found to be associated with more severe crashes. According to the marginal effects, wider shoulders reduce the probability of no injury or slight injury by 33% and 6%, respectively, but increase the probability of serious and fatal injuries by 27% and 12%, respectively. As an explanation for this result it was suggested that wider shoulders might encourage higher travel speeds and thus increase the risk of severe crashes.

Khan et al. (2015) fitted a safety performance function for run-off-the road crashes on two-lane highways in Idaho. For the paved right shoulder width a set of dummy variables was introduced such as: up to 2 feet, 3–4 feet, and 5 feet or wider (the base category). The model showed that the crash risk was lowest for the base category and higher for both categories of narrower shoulders (< 5 feet). However, the risk associated with shoulder width was not linear in nature.

Evidently, the form of the relationship between the shoulder width and crashes is not simple and may change in various ranges of shoulder width. Various forms of relations can be observed depending on road conditions and crash types.

## 3. Methodology

### 3.1. The study database

This study included the majority on the two-lane non-urban road network in Israel. The study database was prepared by means of combining information from the Central Bureau of Statistics' (CBS) crash files and road characteristics' files of the National Transport Infrastructure Company (NTIC). The NTIC is responsible for construction, maintenance, upgrading and extension of the non-urban road network in the country (except for several freeways, which are controlled by other operators). The information on geometric and other road infrastructure characteristics came from the 2010 NTIC road survey. The NTIC data are collected for segments of 100 m in length. Due to limited accuracy in reporting crash locations by the police, for the current study, the segments were combined into road sections of about 1 km in length. For each section, a range of infrastructure characteristics was produced, including total shoulder width, unpaved (granular) shoulder width, lane width, speed limit, horizontal radius,

convex and concave vertical radii, vertical grade, and the "safety level" of roadsides.

The characteristics of road sections were produced as follows: for lane width and shoulder width, an average value, across the segments composing the road section, was estimated; for each type of radius - a minimum value, as an average of the three lowest values across the segments, and for vertical grade - a maximum value, as an average of the three highest values across the segments, was provided (all estimates included both travel directions together). Furthermore, for each characteristic, a number of categories was defined based on the existing design guidelines for two-lane roads (MOT, 2012), to differentiate gradually between the lowest and best design standard, and for each road section a certain category was assigned, respectively. For shoulder characteristics, similarly to Gross and Donnell (2011), two values were defined, the total shoulder and unpaved shoulder widths, where the total width presents a sum of paved and unpaved shoulders.

The use of average values of lane width and shoulder width is common in practice to characterize the layout of short road sections. In general, the precision of a measure can be assessed by calculating the coefficient of variation (CV), which is the ratio of standard deviation and mean of the measure, across the dataset examined (AASHTO, 2010). A small CV indicates a high level of precision in the estimate, while the default value of 0.5 can be judged as appropriate. The examinations of the study database showed that, for average values of lane width, the mean CV was 0.05, while 99% of the study sections had CV values below 0.19; for average values of total shoulder width, the mean CV was 0.27, while for 88% of the units the CV values were below 0.5. This indicates that the values of lane width and shoulder width were not diverse in the majority of the study units and, hence, average values can represent these characteristics.

For roadside conditions, eight categories of "safety level" were defined depending on the presence or absence of safety barriers on the roadsides. When barriers' presence on a road section was dominant (i.e. on more than half of the section length), the barrier's position was examined, including the distance from the right traffic lane to the barrier and the free space behind the barrier and in front of rigid obstacles; otherwise, in the case of no barriers on roadsides for most of the section, the recovery zone width was considered. In both cases, four categories were defined, from 1 to 4 and from 5 to 8, respectively, where categories "1" and "5" corresponded to the lowest level and categories "4" and "8" - to the best design standard, according to the guidelines (MOT, 2012). Specifically, category "1" reflected a barrier's position up to 1 m from the right traffic lane, "2" - 1–2 m from the traffic lane, "3" - over 2 m from the lane and free space behind the barrier up to 1 m, "4" - over 2 m from the lane and free space behind the barrier over 1 m; category "5" - the width of recovery zone up to 3 m, "6" - between 3 and 5.5 m, "7" - between 5.5 and 7.5 m, "8" - 7.5 m or over. A variety of characteristics of the road sections was considered by the study in order to exclude the impact of possible confounding factors while evaluating the impact of shoulders, as was suggested in previous research (Hauer, 2000; Stamatidis et al., 2009; Gross and Donnell, 2011).

The data on crash frequencies, on each road section, were collected for three years, 2008–2010 (the time frame corresponding to road characteristics), according to several crash types: injury crashes, single-vehicle crashes, vehicle collisions, severe crashes (fatal and serious together) and total crashes. The last group presents a sum of two crash files, which are collected by the Israeli police: an "injury crash" file, with cases investigated by the police examiners, and a "general with casualties" file, with cases reported to the police but not investigated. The first file includes all injury severity levels and serves as a basis for the official crash figures; the second file includes cases with slight injuries only (not hospitalized), which do not satisfy the selection criteria of the "injury" file. As the amount of records in the second file versus the first usually presents a 80% to 20% relation, both files were included in the analysis. Single-vehicle crashes included "leaving the roadway", "overturn" and "collision with fixed object" types, which in

**Table 1**  
Descriptive statistics of the study sections.

Continuous variables	Name	Min	Max	Mean	S.d.
No to injury crashes per section, in 3 years	–	0	14	0.75	1.41
No of single-vehicle crashes per section, in 3 years	–	0	5	0.18	0.48
No of vehicle collisions per section, in 3 years	–	0	10	0.53	1.14
No of severe crashes per section, in 3 years	–	0	5	0.20	0.53
No of total crashes per section, in 3 years	–	0	24	2.04	3.42
Section length, km	length	0.10	1.14	0.92	0.19
Total shoulder width, m	sh_to_w	0.0	5.16	1.83	0.85
Unpaved shoulder width, m	sh_gr_w	0.0	4.39	0.43	0.59
Categorical variables	Categories (proportion of sample, %)				
Average daily traffic (AADT), thousands of vehicles	below 3 (35.1%), 3-6 (26.0%), 6-9 (21.2%), 9-12 (4.7%), 12-15 (4.1%), over 15 (8.9%)				
Speed limit, kmh	70 or below (15.8%), 80 (57.2%), 90 (27.0%)				
Convex vertical radius, m	below 1800 (39.1%), 1800-3000 (19.7%), 3000-5000 (17.0%), 5000-7250 (8.4%), over 7250 (15.9%)				
Concave vertical radius, m	below 1700 (37.6%), 1700-2400 (14.8%), 2400-3200 (12.4%), 3200-4000 (8.1%), over 4000 (27.0%)				
Horizontal radius, m	below 120 (3%), 120-190 (5%), 190-270 (7%), 270-380 (9%), over 380 (76%)				
Lane width, m	below 2.8 (8.5%), 2.8-3.2 (25.5%), over 3.2 (66.1%)				
Total shoulder width, m	below 0.9 (13.4%), 0.9-1.2 (10.2%), 1.2-1.5 (12.4%), 1.5-1.8 (15.0%), 1.8-2.1 (14.9%), 2.1-2.4 (10.3%), 2.4-2.7 (8.4%), 2.7-3.0 (5.9%), over 3 (9.4%)				
Unpaved shoulder width, m	below 0.9 (81.0%), 0.9-1.2 (6.7%), 1.2-1.5 (5.0%), 1.5-1.8 (3.8%), over 1.8 (3.5%)				
Roadside conditions (safety level)	Based on the placement of safety barriers: [1] low (0.5%), [2] medium (10.8%), [3] good (20.5%), [4] very good (7.4%) Based on the width of recovery zone <sup>b</sup> : [5] low (19.1%), [6] medium (31.0%), [7] good (8.6%), [8] very good (2.2%)				
Vertical grade, %	below 3 (45.3%), 3-5 (22.7%), 5-8 (21.4%), 8-10 (7.5%), 10-12 (2.6%), over 12 (0.6%)				

<sup>a</sup> When safety barriers are present on over 50% of the section length.  
<sup>b</sup> otherwise.

sum reflect the run-off-road crashes, in Israel. Vehicle collisions included all multiple-vehicle crashes (i.e. excluding single-vehicle crashes and pedestrian crashes from all injury crashes). For each crash type, only section crashes were counted, excluding junctions. The types of crashes selected for examination in this study were defined accounting for the crash types that were used for exploring shoulder impacts in previous research (Hauer, 2000; Stamatiadis et al., 2009; Gross and Donnell, 2011; Khan et al., 2015) but, also, for the possibilities and limitations of local crash statistics.

The values of traffic volumes on the study sections were extracted from the CBS files in the form of the average annual daily traffic (AADT), over the years 2008–2010. The study's database comprised 3594 road sections with a total length of 3302 km. Over the three-year period, on the study sections 2678 injury crashes occurred, of which 725 (27%) were severe crashes, 644 (24%) - single-vehicle crashes and 1903 (71%) - vehicle collisions; the number of total crashes (from both crash files) was 7349. Table 1 presents descriptive statistics of the study database.

### 3.2. Development of explanatory models

Exploring the impacts of shoulder characteristics on crashes should account for other road and traffic characteristics. Thus, multivariable statistical models can be developed for a relationship between shoulder characteristics and crashes, controlling for other road characteristics and traffic exposure. Many previous studies found the effects of shoulder characteristics on crashes by fitting multivariable statistical models (Zegeer et al., 1988; Council and Stewart, 1999; Qin et al., 2004; Mallschutzke et al., 2006; Khan et al., 2015), i.e. applied a cross-sectional approach. This approach was generally criticized (Hauer, 2010), as in fitting multivariable models an unknown amount of confounding factors can be present and, thus, hinder the identification of a cause-effect relation. Observational before-after studies were stated as preferable to ascertain the impact of safety countermeasures (Hauer, 2010). However, a before-after approach was not applicable in the current study, due to the practical impossibility to accumulate road sites where shoulder characteristics were changed, with corresponding periods before and after the treatment, as frequently happens while exploring road design characteristics. Hence, we considered the use of a case-control study design, which is an observational epidemiological approach (Woodward, 2005) and enables to reduce some limitations of the cross-sectional approach.

In the case-control design, two data sets are extracted from the original data based on the outcome status: *cases* – locations that experienced at least one crash in the study period, and *controls* – locations that did not experience crashes in the same period. Each *control* site is randomly matched to each *case* site based on several factors that can serve as potential confounders for crash occurrences. The matching provides a balanced design and controls for the effects of variables included in the matching scheme. Then, a conditional regression model is fitted to the combined *case-control* dataset, to assess whether exposure to the examined risk factor is disproportionately distributed between *cases* and *controls*, thereby indicating the likelihood of an outcome given the presence of the risk factor. The model enables to estimate the odds ratio, which is a measure of the percent change in the chance of an outcome given the presence of a risk factor compared to the baseline level of the risk factor. The conditional regression model may also control for additional factors, which are present in both sets but were not applied in the matching scheme.

Previous studies (Gross and Jovanis, 2007; Gross and Donnell, 2011) demonstrated the applicability of the case-control (CC) method for assessing the safety effects of shoulders and other road characteristics, in several US States. It was indicated that the odds ratio produced by the CC method may serve as an approximation of crash modification factors because it provides an estimate of the incremental safety effect of a particular feature in relation to a certain baseline level.

Conditional binary logistic regression is used to estimate the odds ratio for the matched case-control design. Suppose we have  $J$  matched sets, with  $n_{1j}$  cases and  $n_{0j}$  controls in set  $j$ ,  $j = 1, 2, \dots, J$ . For the set  $j$ 's specific logistic regression model, the probability of a crash is given by Eq. (1):

$$P_j(Y = 1) = 1 / \left\{ 1 + \exp \left[ - \left( \alpha_j + \sum_{i=1}^p \beta_i x_i \right) \right] \right\} \quad (1)$$

where  $\alpha_j$  denotes the contribution of all terms constant within the  $j^{\text{th}}$  set (i.e. the matching variables);  $\beta_i$  ( $i = 1, 2, \dots, p$ ) are estimated coefficients for unmatched explanatory variables;  $x_i$  ( $i = 1, 2, \dots, p$ ) are unmatched explanatory variables (Hosmer et al., 2013). The conditional likelihood for the  $j^{\text{th}}$  set ( $l_j(\beta)$ ) is obtained from the probability of the observed data conditional on the set's total and the set's total number of cases observed.

However, when the matched design is one in which each *case* is matched to a single *control*, there are two subjects in each set, and the conditional likelihood for the  $j^{\text{th}}$  set is reduced to:

$$\begin{aligned} l_j(\beta) &= \frac{\exp(\sum_{i=1}^p \beta_i x_{i1j})}{\exp(\sum_{i=1}^p \beta_i x_{i1j}) + \exp(\sum_{i=1}^p \beta_i x_{i0j})} \\ &= \frac{1}{1 + \exp(\sum_{i=1}^p \beta_i x_{i0j} - \sum_{i=1}^p \beta_i x_{i1j})} = \frac{1}{1 + \exp(-\sum_{i=1}^p \beta_i (x_{i1j} - x_{i0j}))} \end{aligned} \quad (2)$$

where  $x_{i0j}$  is the unmatched  $i^{\text{th}}$  explanatory variable value for the *control* in  $j^{\text{th}}$  set,  $x_{i1j}$  is the unmatched  $i^{\text{th}}$  explanatory variable value for the *case* in  $j^{\text{th}}$  set.

The full conditional likelihood is the product of the  $l_j(\beta)$  in Eq. (2) over the  $J$  sets, and equals:

$$l(\beta) = \prod_{j=1}^J l_j(\beta) = \prod_{j=1}^J \frac{1}{1 + \exp(-\sum_{i=1}^p \beta_i (x_{i1j} - x_{i0j}))} \quad (3)$$

Estimates of the coefficients for the explanatory variables are obtained by maximizing the likelihood expression in Eq. (3).

The odds ratio between any two values ( $x_A$  and  $x_B$ ) of a risk factor is estimated as follows:

$$\text{odds ratio} = \exp(\beta_A x_A - \beta_B x_B) \quad (4)$$

where  $\beta_A$  and  $\beta_B$  are model coefficients associated with the risk factor values.

In the current study, the *case* and *control* road sections were matched using four characteristics (potential confounders) such as: AADT, speed limit, convex vertical radius and concave vertical radius, whereas other variables (see Table 1) served for the model development. A one-to-one ratio was used for the matching as is common in case-control studies (Woodward, 2005). The combined dataset included 2010 road sections (1050 cases and 1050 controls). A conditional binary logistic regression was applied, using the Logistic procedure of SAS. The procedure of building CC-models in the current study is illustrated in Fig. 1. The characteristics applied for matching CC pairs and those used for a consequent model fitting are indicated.

However, CC models cannot be used to measure the probability of an event in terms of expected frequency (Gross and Jovanis, 2007; Gross and Donnell, 2011). Thus, in addition to the CC models, common multivariable regression models were fitted to crash counts on the road sections, using generalized linear modelling techniques (Hauer, 2015). A negative binomial (NB) regression model was fitted to crashes, with a logarithmic relation between the explanatory variables and the expected value of the dependent variable. If  $Y_i$  represents the expected number of crashes on section  $i$ , then the model is expressed as:

$$\begin{aligned} Y_i &\sim \text{NB}(\lambda_i, k) \\ \lambda_i &= E(Y_i) = \exp(\beta_0 + X_i \beta) \end{aligned} \quad (5)$$

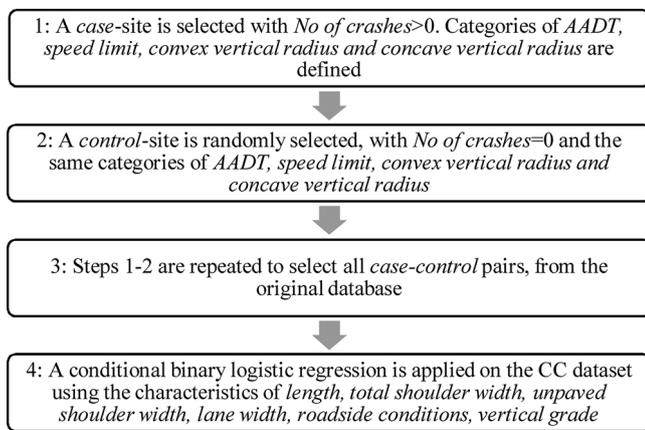


Fig. 1. The procedure of building CC-models in the current study.

where  $X_i$  is the vector of explanatory variables (section characteristics),  $\beta$  is the vector of parameters to be estimated (model coefficients),  $k$  is the scale parameter for the NB distribution, i.e.  $\text{Var}(Y_i) = \lambda_i + k\lambda_i^2$ . The model estimates the expected number of crashes on a section during the three years' period. The model parameters were estimated using the GENMOD procedure of SAS, allowing for second order interactions between the explanatory variables. The NB regression models were developed using the whole study database (3594 units).

Based on the NB model, a crash modification factor (CMF) can be estimated for each section characteristic, which reflects the change in safety following a change in a road design element. The way of CMF estimation is similar to Eq. (4) but uses coefficients for the respective values of the variable in the NB model.

The CC and NB models were developed for each crash type separately. Those are univariate models enabling different impacts of explanatory variables on different crash types (see an overview of modelling approaches, e.g., in Hosseinpour et al., 2014. An alternative multivariate approach with simultaneous modelling of several crash types was not tried as the study's purpose was to explore the impacts of shoulder characteristics on various crash types). In each case, two variants of models were fitted, i.e. using continuous or categorical values of shoulder variables, and then the variant with higher significance of shoulder variables was selected.

Prior to the development of parametric models, the form of relationship between crashes and each shoulder characteristic was explored using plots, as is common in generalized additive models (Wood, 2006). When a non-linear relation is suspected in the data, the need for a piecewise-linear approximation (Hastie et al., 2009) is considered and two ranges of values of the predicting variable are defined subdivided by a "breaking point" (where the form of the relation may change). In this study, based on the behaviors observed for categorical shoulder variables, "breaking points" enabling different slopes for different intervals of values of the continuous shoulder characteristics were defined. As "breaking points" were selected the values of 2.25 and 0.9, for total shoulder width and unpaved shoulder width, respectively. Thus, in the models using continuous shoulder variables, a piecewise-linear relation of each variable to crashes was fitted, i.e. with two coefficients, one reflecting the impact of shoulder width below the "breaking point" and a second one reflecting the impact of shoulder width for values higher than the "breaking point".

4. Results

4.1. A case-control model for injury crashes

Table 2 presents a CC model fitted to injury crashes; the model with continuous shoulder variables was preferred due to a higher significance of shoulder effects. As indicated previously, the "breaking

Table 2 Case-control model for injury crashes.

Variable	Estimate	Standard Error	Wald Chi-Square	Pr > ChiSq
Logarithm of length	2.176	0.307	50.376	< .0001
sh_to_w_low <sup>#</sup>	0.170	0.118	2.076	0.150
sh_to_w_H <sup>#</sup>	-0.347	0.176	3.882	0.049
sh_gr_w_low <sup>#</sup>	-0.211	0.181	1.354	0.245
sh_gr_w_H <sup>#</sup>	0.463	0.244	3.588	0.058
Lane width: below 2.8	-0.578	0.207	7.831	0.005
Lane width: 2.8-3.2	-0.292	0.120	5.921	0.015
Lane width: over 3.2	0			
Roadside conditions: category 2	1.281	0.417	9.458	0.002
Roadside conditions: category 3	1.149	0.400	8.251	0.004
Roadside conditions: category 4	0.868	0.418	4.323	0.038
Roadside conditions: category 5	1.028	0.409	6.316	0.012
Roadside conditions: category 6	0.739	0.393	3.532	0.060
Roadside conditions: category 7	0.685	0.409	2.797	0.095
Roadside conditions: category 8	0			
Vertical grade: below 3	0.342	0.520	0.433	0.511
Vertical grade: 3-5	0.583	0.522	1.247	0.264
Vertical grade: 5-8	0.600	0.523	1.316	0.251
Vertical grade: 8-10	0.640	0.534	1.439	0.230
Vertical grade: 10-12	0.946	0.572	2.733	0.098
Vertical grade: over 12	0			

Notes: <sup>#</sup>For shoulder variables: there are "breaking points" at 2.25 and 0.9 values, for total and unpaved shoulders, respectively; coefficients xxx\_low are applicable before, xxx\_H - after the breaking points. In each case, applying the model, from the original values of shoulder width should be subtracted: 2.25 from sh\_to\_w, 0.9 - from sh\_gr\_w.

points" were introduced for shoulder variables, hence, the model shows different effects for lower and higher values of both shoulder characteristics. In this model, overall (based on the Type 3 analysis of effects), a significant impact on crashes was found for section length, higher values of the total shoulder width, lane width and roadside conditions (with  $p < 0.05$ ). In addition, a close to significant impact (with  $p < 0.10$ ) was found for higher values of the unpaved shoulder width and vertical grade, whereas the impacts of lower values of the total and unpaved shoulder widths were not significant.

The model indicates an increase in crash risk when the total shoulder width increases up to 2.25 m and a consequent decrease in crash risk when the shoulder width grows further, over 2.25 m. Conversely, an initial increase in unpaved shoulder width, up to 0.9 m, is associated with a decrease in crash risk, whereas a further increase in the unpaved shoulder width, over 0.9 m, brings an increase in crashes. Concerning other road characteristics, the model indicates a higher crash risk for wider lane width, over 3.2 m, whereas for narrower lanes a decrease in crash risk is expected. A gradual increase in the crash risk for sections with a higher vertical grade was found (unexpectedly, the category with the highest vertical grade was not associated with a highest crash risk, however, the data showed that this category was represented by a small number of cases). Regarding the roadside conditions, the model shows that lower crash risk is associated with sections having fewer safety barriers and better recovery zones. Among sections with a higher presence of safety barriers on roadsides, lower crash risk is associated with better barrier placement, i.e. when the barrier is remote from the roadway and relevant space is provided behind the barrier and in front of the obstacles.

Fig. 2a and b, illustrates the relative change in injury crash risk (odds ratios, Eq. (4)) associated with changes in the total shoulder width and in the unpaved shoulder width, respectively. Based on the

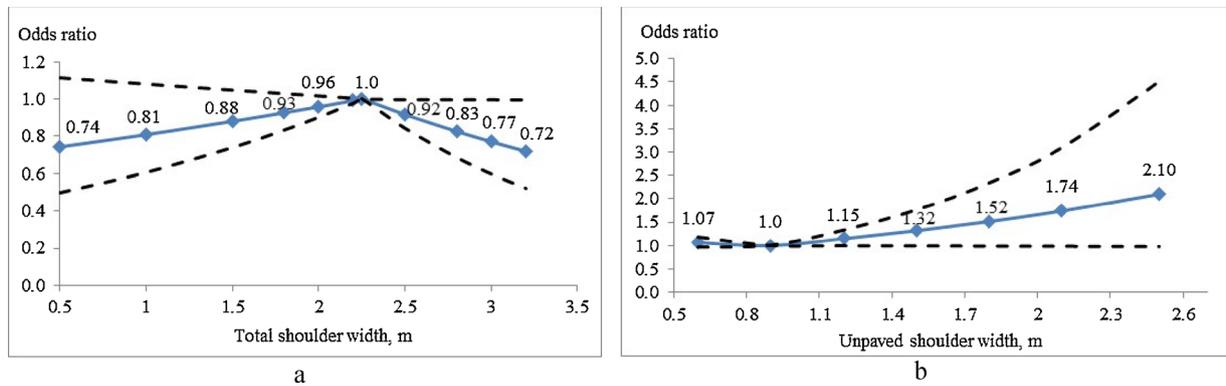


Fig. 2. Relative change in injury crash risk associated with changes in width of: (a) total shoulder, (b) unpaved shoulder.

Table 3

Relative changes in injury crash risk following a combined change in both shoulder characteristics, versus baseline conditions: total shoulder width – 2.25 m, unpaved shoulder – 0.9 m.

Unpaved shoulder width, m	Total shoulder width, m									
	0.9	1.2	1.5	1.8	2.1	2.25	2.4	2.7	3	3.2
0.9	0.80	0.84	0.88	0.93	0.97	1.0	0.95	0.86	0.77	0.72
1.2		0.96	1.01	1.06	1.12	1.15	1.09	0.98	0.89	0.83
1.5			1.16	1.22	1.29	1.32	1.25	1.13	1.02	0.95
1.8				1.41	1.48	1.52	1.44	1.30	1.17	1.09
2.1					1.70	1.74	1.65	1.49	1.34	1.25

model estimates, the mean values of risk changes and their confidence intervals ( $\pm 1.96$  standard error) are provided. Table 3 demonstrates the relative changes in injury crash risk following a combined change in both shoulder characteristics. In Fig. 2 and Table 3 the relative changes are given versus baseline conditions: a total shoulder of 2.25 m in width, unpaved shoulder - of 0.9 m. The results show that within the range of initial increase in the total shoulder width (up to 2.25 m), each shoulder extension by 0.1 m is associated with crash increase by 1.7%, while for higher total shoulder width (over 2.25 m), each shoulder extension by 0.1 m is associated with crash decrease by 3.4%. Similarly, we find that for greater unpaved shoulder width (over 0.9 m), each extension of the unpaved shoulder by 0.1 m is associated with a crash increase by 4.7%.

It follows that on two-lane local roads, the lowest crash risk is attained on sections with narrow shoulders (below 1 m in total) that do not allow vehicles to stop, and on sections with full shoulders (about 3 m or more) that enable safe vehicle stops without disturbing traffic in the adjacent lane. On the other hand, the intermediate values of the total shoulder width (between 1–3 m) and, particularly, the values between 2–2.5 m, are associated with an increase in crash risk and, thus, should be avoided. Additionally, the extension of unpaved shoulder (over the minimum value of 0.9 m) within the total shoulder width will bring to an increase in crash risk.

4.2. Comparisons with a negative-binomial model for injury crashes

Table 4 presents the NB model fitted to injury crashes, with categorical shoulder variables. (The models with continuous and categorical shoulder variables were almost identical in terms of criteria of goodness of fit; the variable of unpaved shoulder width showed a marginal significance in the second model and was not significant in the first, thus, the model with categorical shoulder variables was selected for presentation). Only first order model coefficients are given in Table 4, and the second order interactions are omitted.

In this model, in general (based on the Wald statistics for Type 3 analysis), a significant impact on crashes was found for section length,

AADT, speed limit, lane width and roadside conditions (with  $p < 0.05$ ); a close to significant impact (with  $p < 0.10$ ) – for total shoulder width; the impacts of other features were insignificant. The model indicates that the number of crashes increases with an increase in section length and traffic volume (as expected), for lower speed limits and wider lane width (the impact of lower speed limits probably reflects worse geometric conditions; the impact of wider lanes – higher travel speeds). As to the roadside conditions, lower crash numbers are generally expected on sections with fewer safety barriers and better recovery zones. Higher vertical grade is associated with higher crash numbers. In general, the impacts of road characteristics in the NB model for injury crashes resemble those found by the CC model.

With regard to shoulder characteristics, the NB model indicates an initial increase in crash numbers and a consequent decrease, following the total shoulder extension, whereas highest crash frequencies are associated with the width of 1.5–2.4 m. The number of crashes generally increases with an increase in the unpaved shoulder width, yet, fewer crashes are expected for the values of 0.9–1.5 m.

Fig. 3a–b, compares the relative changes in injury crash risk (odds ratios) and in the expected injury crash numbers (CMF) following the changes in shoulder characteristics, as reflected in the coefficients of both models; the relative changes were estimated versus the baseline values: 2.25 m for total shoulder, 0.9 m for unpaved shoulder. One can note that the effects of the total shoulder width are close in both models, indicating a higher risk for the intermediate values (between 1.5–2.4 m) and a lower risk for a very narrow or wide shoulder; also, the CC model tends to predict slightly higher changes in crash risk as opposed to the NB model. Concerning the impact of the unpaved shoulders, both models generally indicate an increase in crash risk with an increase in the unpaved shoulder width, however, the effect shown by the CC model is stronger. Admitting that the method of building the CC model more clearly accounted for the confounding factors and that the effect of this characteristic in the CC model is more significant, related to the NB model, it follows that the impact found by the CC model can be more trusted.

4.3. Overview of models for other crash types

Tables 5 and 6 provide a summary of the CC and NB models fitted to other crash types. In all the cases, the models with continuous shoulder variables were selected due to more pronounced effects of shoulder characteristics, compared to models with categorical shoulder variables. (In all models for vehicle collisions, the impacts of shoulders were not significant and, therefore, they are not presented here). The results show that all the models were consistent with regard to the impact of the total shoulder width, where an initial increase in the width up to 2.25 m was associated with an increase in crash risk but further shoulder widening – with a decrease in the risk, and this relationship was mostly significant, particularly in the CC models. The

**Table 4**  
Negative-binomial regression model for injury crashes.

Variable	Estimate	StdErr	ChiSq	ProbChiSq
Intercept	-0.14	0.65	0.04	0.84
Logarithm of length	1.22	0.15	66.25	< 0.001
AADT: below 3	-3.10	0.41	58.55	< 0.001
AADT: 3-6	-1.48	0.36	17.39	< 0.001
AADT: 6-9	-1.36	0.33	16.76	< 0.001
AADT:9-12	-1.68	0.62	7.30	< 0.01
AADT: 12-15	-0.57	0.40	2.08	0.15
AADT: over 15	0			
Speed limit: 70 or below	0.58	0.36	2.57	0.11
Speed limit: 80	0.34	0.33	1.08	0.30
Speed limit: 90	0			
Convex vertical radius: below 1800	-0.22	0.33	0.44	0.50
Convex vertical radius: 1800-3000	0.50	0.36	2.00	0.16
Convex vertical radius: 3000-5000	0.32	0.35	0.85	0.36
Convex vertical radius: 5000-7250	0.09	0.45	0.04	0.83
Convex vertical radius: over 7250	0			
Concave vertical radius: below 1700	0.10	0.29	0.12	0.73
Concave vertical radius: 1700-2400	0.11	0.36	0.09	0.77
Concave vertical radius: 2400-3200	0.45	0.37	1.46	0.23
Concave vertical radius: 3200-4000	-0.25	0.45	0.32	0.57
Concave vertical radius: over 4000	0			
Total shoulder width: below 0.9	-0.16	0.16	0.95	0.33
Total shoulder width: 0.9-1.2	0.13	0.16	0.70	0.40
Total shoulder width: 1.2-1.5	0.07	0.15	0.24	0.62
Total shoulder width: 1.5-1.8	0.18	0.14	1.79	0.18
Total shoulder width: 1.8-2.1	0.18	0.13	1.78	0.18
Total shoulder width: 2.1-2.4	0.16	0.14	1.42	0.23
Total shoulder width: 2.4-2.7	0.15	0.14	1.21	0.27
Total shoulder width: 2.7-3.0	-0.02	0.15	0.01	0.92
Total shoulder width: over 3	0			
Unpaved shoulder width: below 0.9	-0.24	0.21	1.28	0.26
Unpaved shoulder width: 0.9-1.2	-0.38	0.24	2.49	0.11
Unpaved shoulder width: 1.2-1.5	-0.43	0.25	2.80	0.09
Unpaved shoulder width: 1.5-1.8	-0.02	0.26	0.00	0.95
Unpaved shoulder width: over 1.8	0			
Lane width: below 2.8	-0.46	0.15	9.51	< 0.01
Lane width: 2.8-3.2	-0.19	0.08	5.96	0.01
Lane width: over 3.2	0			
Roadside conditions: category 1	0.16	0.60	0.07	0.79
Roadside conditions: category 2	0.95	0.30	10.00	< 0.01
Roadside conditions: category 3	0.96	0.29	10.68	< 0.01
Roadside conditions: category 4	0.76	0.30	6.38	0.01
Roadside conditions: category 5	0.84	0.30	8.00	< 0.01
Roadside conditions: category 6	0.69	0.29	5.76	0.02
Roadside conditions: category 7	0.40	0.30	1.72	0.19
Roadside conditions: category 8	0			
Vertical grade: below 3	0.04	0.42	0.01	0.92
Vertical grade: 3-5	0.14	0.42	0.11	0.74
Vertical grade: 5-8	0.17	0.42	0.17	0.68
Vertical grade: 8-10	0.29	0.43	0.47	0.49
Vertical grade: 10-12	0.33	0.46	0.54	0.46
Vertical grade: over 12	0			

Notes: Interactions of second order are not presented. Model statistics: deviance = 2888.5, df = 3342, scale = 0.864; dispersion = 0.695 (0.060). Wald statistics for Type 3 analysis: *total shoulder width* (p = 0.092), *unpaved shoulder width* (p = 0.25).

results concerning the impact of the unpaved shoulder width were inconsistent and insignificant for single-vehicle and severe crashes. For total crashes, the impact of the unpaved shoulders was significant and resembling the findings for injury crashes, i.e. with a decrease in crash risk for the width below 0.9 m and an increase in crashes for a wider unpaved shoulder.

Concerning other road characteristics, in the CC models, a significant impact on crashes was found for section length (in all crash types) as well as for lane width and roadside conditions (in severe and total crashes). Simultaneously, in the NB models, a significant impact on various crash types was found for section length, traffic volume, speed limit, lane width and roadside conditions, and also for vertical grade (in severe and total crashes). The models show that wider lane

width, over 3.2 m, is associated with higher risk for single-vehicle and severe crashes related to narrower lanes, apparently, due to higher travel speeds invited by wider lanes, while to reduce total crashes, the lane width between 2.8 and 3.2 m is preferable. Regarding the roadside conditions, the lowest crash risk is associated with high standard recovery zones (particularly, for severe crashes), and additional lower risk – with properly placed safety barriers on the roadsides (i.e. when the barrier is distant from the roadway and with sufficient working space behind). Both cases reflect more forgiving roadside conditions. Similarly to findings for injury crashes, the numbers of other crashes increase with an increase in section length and in traffic volume, and also on sections with lower speed limits, which probably reflect the presence of infrastructure constraints. The impact of vertical grade was inconsistent among various crash types but generally indicated an increase in single-vehicle and total crashes on sections with stronger grades.

Fig. 4a–d, compares the relative changes in crash risk (odds ratios) and in the expected crash numbers (CMF) following the changes in shoulder characteristics, as reflected in the CC and NB models fitted to single-vehicle, severe and total crashes. Only significant effects are illustrated, i.e. relative changes in all crash types following a widening of the total shoulder and relative changes in total crashes following a widening of the unpaved shoulder; the crash changes are given related to the baseline values: 2.25 m for total shoulder, 0.9 m for unpaved shoulder. The effect of the total shoulder width appears to be similar for various crash types, yet, the initial increase in crash risk (within shoulder widening up to 2.2 m) is stronger compared to injury crashes, particularly for single-vehicle and total crashes. On the other hand, severe crashes are less sensitive to the shoulder widening over 2.8 m, compared to other crash types. The effect of changes in the total shoulder width on single-vehicle and total crashes is stronger in CC-models compared to NB-models and is probably more trustable due to better treatment of confounding factors in the CC models.

The results in Fig. 4 indicate that higher crash risk (of specific crash types) is associated with the intermediate values of the total shoulder width in the range of 2–2.5 m, while a lower risk is expected for narrow shoulders below 1.8 m and for wide shoulders of over 2.8 m. Concerning the impact of the unpaved shoulders on total crashes, the effects shown by the CC and NB models are very close, while, similarly to previous cases, the effect of the CC model is slightly stronger. Moreover, the impact of the unpaved shoulder on total crashes is close to that found by the CC model for injury crashes indicating an increase in crash risk with an increase in the unpaved shoulder width over 0.9 m. It can be estimated that within the initial range of the total shoulder width (up to 2.25 m), each shoulder extension by 0.1 m is associated with an increase by 5.8%, 3.4% and 6.3% in single-vehicle, severe and total crashes, respectively, while for higher total shoulder width (over 2.25 m), each shoulder extension by 0.1 m is associated with a respective crash decrease by 4.0%, 0.9% and 2.4%. Similarly, for the unpaved shoulder over 0.9 m, each width extension by 0.1 m is associated with total crash increase by 5.2%.

## 5. Discussion

This study was initiated to examine the relationship between shoulder width (and type) and crash occurrences, on two-lane rural roads in Israel, while accounting for impacts of other road and traffic characteristics. This topic was not explored in the past, for local conditions. The background literature indicated that a prevailing form of relationship, particularly in the American experience, was a monotonous decreasing link between the shoulder width and crashes, yet, questions can be raised when the detailed data or findings of some previous studies are considered. The current study, as expected, found a significant relationship between the shoulder characteristics and crash risk, on two-lane local roads. However, the study did not support a monotonous link between the increase in shoulder width and a decrease

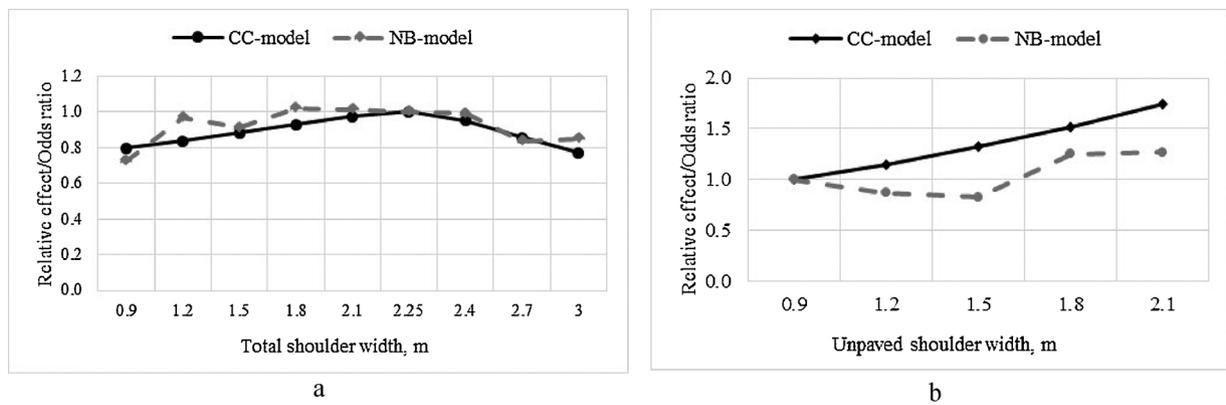


Fig. 3. Comparison of relative changes in injury crash risk based on CC vs NB models: (a) for changes in total shoulder width, (b) for changes in unpaved shoulder width.

in crashes as was reported in previous research (Zegeer et al., 1981, 1988; Harwood et al., 2000; Stamatias et al., 2009; AASHTO, 2010), but found a “broken” link showing that an initial widening that does not attain the full shoulder width (as defined by the design guidelines) is harmful to safety. According to the study results, the impact of the total shoulder width on crashes was generally consistent across various models and crash types showing an increase in crash risk with an initial shoulder extension, up to 2.2 m, and a decrease in crashes with a further shoulder widening beyond this value. The signs of a non-monotonous link between the shoulder width and crashes can be seen in the detailed data or findings of some studies (Zegeer et al., 1980, 1981; Hauer, 2000; Prinsloo and Goudanas, 2003; Qin et al., 2004; Gross and Donnell, 2011), however, such a non-monotonous relation was not explicitly stated in the previous research literature.

The study also found that, for injury and total crashes, an increase in the width of unpaved (granular) shoulder, over 0.9 m, leads to an increase in crash risk. This result is in line with previous research which reported that roads with paved shoulders were usually associated with fewer crashes (Hauer, 2000; World Road Association, 2003).

According to the majority of the findings, lowest crash risks are associated with a shoulder width of about 3 m or more, with no or narrow unpaved shoulders, that is in line with the existing literature

(AASHTO, 2010; World Road Association, 2003). In addition, the lowest crash risk was also associated with narrow total shoulders, below 1 m, which is not common in the literature. The latter may reflect the impact of a constrained road layout that reduces vehicle speeds and thus may be beneficial to safety (Gitelman et al., 2016). Both sizes of the total shoulders, the wide and the narrow one, may be recommended for application, based on safety and traffic concerns. Conversely, medium total shoulders, of 1.8–2.4 m in width, and unpaved shoulders of over 1 m, were associated with an increase in the crash risk and, hence, are not recommended for use.

From the viewpoint of drivers’ perception, the study’s results may be considered as reasonable because very narrow shoulders usually prevent vehicle stops, while wide shoulders (of 3 m or more) are perceived and function as safe for stopping and crash avoiding maneuvers. At the same time, medium-sized shoulders may be perceived as sufficient for a stop by some drivers thus, inviting hazardous conditions when unexpected obstacles appear in close proximity to the roadway or even protrude into the traffic lane.

While considering safety measures of shoulder widening or sealing for a road section, the road designer can apply the study estimates. For example, it was found that the total shoulder extension by 0.1 m is associated with injury crash increase by 1.7%, when the shoulder is

Table 5  
Case-control models for other crash types.

Variable	Single-vehicle crashes		Severe crashes		Total crashes	
	Estimate	Standard Error	Estimate	Standard Error	Estimate	Standard Error
Logarithm of length	1.222*	0.327	2.052*	0.379	1.572*	0.250
sh_to_w_low#	0.565*	0.169	0.339**	0.163	0.613*	0.110
sh_to_w_H#	-0.410***	0.238	-0.095	0.226	-0.240***	0.142
sh_gr_w_low#	-0.149	0.258	0.002	0.263	-0.670†	0.159
sh_gr_w_H#	-0.087	0.327	-0.343	0.377	0.506**	0.163
Lane width: below 2.8	-0.559***	0.332	-0.578***	0.336	0.081	0.157
Lane width: 2.8-3.2	-0.257	0.174	-0.336***	0.175	-0.489†	0.108
Lane width: over 3.2	0		0		0	
Roadside conditions: category 2	0.667	0.591	1.728**	0.653	0.181	0.318
Roadside conditions: category 3	0.184	0.577	1.764**	0.641	0.312	0.309
Roadside conditions: category 4	0.200	0.602	1.517**	0.653	-0.715**	0.335
Roadside conditions: category 5	0.715	0.585	1.830**	0.651	0.288	0.309
Roadside conditions: category 6	0.186	0.566	1.386**	0.631	-0.166	0.293
Roadside conditions: category 7	0.001	0.606	0.917	0.652	-0.234	0.306
Roadside conditions: category 8	0		0		0	
Vertical grade: below 3	-0.494	1.248	14.230	682.5	-0.439	0.465
Vertical grade: 3-5	-0.394	1.247	14.065	682.5	-0.224	0.466
Vertical grade: 5-8	-0.247	1.247	14.336	682.5	-0.215	0.464
Vertical grade: 8-10	-0.242	1.268	14.362	682.5	-0.177	0.469
Vertical grade: 10-12	0.384	1.326	13.816	682.5	-0.290	0.503
Vertical grade: over 12	0		0		0	

Notes: #For shoulder variables see remarks below Table 2. Significant estimates with \*p < 0.001, \*\*p < 0.05, \*\*\*p < 0.1.

**Table 6**  
Negative-binomial regression models for other crash types.

Variable	Single-vehicle crashes <sup>1</sup>		Severe crashes <sup>2</sup>		Total crashes <sup>3</sup>	
	Estimate	StdErr	Estimate	StdErr	Estimate	StdErr
Intercept	-2.72**	1.12	-22.57*	0.80	1.26**	0.48
Logarithm of length	1.00*	0.26	2.03*	0.29	0.79*	0.11
AADT: below 3	-1.25***	0.69	-2.61*	0.60	-.80*	0.32
AADT: 3-6	0.11	0.61	-1.55**	0.53	-1.66*	0.31
AADT: 6-9	-0.32	0.62	-1.64*	0.50	-1.40*	0.30
AADT:9-12	-0.10	1.01	-1.01	0.94	-1.87*	0.51
AADT: 12-15	-0.87	0.85	-0.31	0.56	-0.49	0.37
AADT: over 15	0		0		0	
Speed limit: 70 or below	0.74	0.68	0.68	0.53	0.38	0.30
Speed limit: 80	0.62	0.60	0.23	0.49	0.12	0.27
Speed limit: 90	0		0		0	
Convex vertical radius: below 1800	0.34	0.61	-0.09	0.49	-0.14	0.29
Convex vertical radius: 1800-3000	0.90	0.63	0.57	0.52	0.13	0.31
Convex vertical radius: 3000-5000	1.10***	0.62	0.13	0.52	0.21	0.30
Convex vertical radius: 5000-7250	1.08	0.72	-0.73	0.73	-0.05	0.37
Convex vertical radius: over 7250	0		0		0	
Concave vertical radius: below 1700	-0.27	0.53	0.01	0.42	0.15	0.25
Concave vertical radius: 1700-2400	-0.17	0.65	0.78	0.50	0.00	0.32
Concave vertical radius: 2400-3200	-0.62	0.73	0.28	0.53	0.36	0.33
Concave vertical radius: 3200-4000	-1.22	0.88	-0.61	0.68	-0.29	0.40
Concave vertical radius: over 4000	0		0		0	
sh_to_w_low <sup>#</sup>	0.35**	0.12	0.32**	0.11	0.29*	0.06
sh_to_w_H <sup>#</sup>	-0.22	0.17	-0.15	0.15	-0.08	0.08
sh_gr_w_low <sup>#</sup>	0.08	0.19	0.08	0.18	-0.30**	0.10
sh_gr_w_H <sup>#</sup>	-0.12	0.26	-0.08	0.25	0.45*	0.11
Lane width: below 2.8	-0.43***	0.24	-0.36	0.24	-0.07	0.11
Lane width: 2.8–3.2	-0.21***	0.12	-0.26**	0.12	-0.21*	0.06
Lane width: over 3.2	0		0		0	
Roadside conditions: category 1	1.06	0.79	0.08	1.13	-0.17	0.44
Roadside conditions: category 2	0.97**	0.46	0.85***	0.49	0.55**	0.20
Roadside conditions: category 3	0.69	0.46	0.89***	0.48	0.63*	0.19
Roadside conditions: category 4	0.52	0.47	0.76	0.49	0.19	0.20
Roadside conditions: category 5	0.82***	0.46	0.87***	0.48	0.49**	0.19
Roadside conditions: category 6	0.65	0.45	0.57	0.47	0.33***	0.19
Roadside conditions: category 7	0.26	0.48	0.32	0.49	0.16	0.20
Roadside conditions: category 8	0		0		0	
Vertical grade: below 3	0.44	0.77	21.48*	0.36	-0.08	0.32
Vertical grade: 3-5	0.54	0.77	21.43*	0.36	-0.02	0.32
Vertical grade: 5-8	0.55	0.77	21.64*	0.36	0.11	0.32
Vertical grade: 8-10	0.63	0.78	21.54*	0.38	0.23	0.33
Vertical grade: 10-12	0.97	0.80	21.27	0.00	-0.03	0.35
Vertical grade: over 12	0		0		0	

Notes: Interactions of second order are not presented. <sup>#</sup>For shoulder variables see remarks below Table 2. Significant estimates with \*p < 0.001, \*\*p < 0.05, \*\*\*p < 0.1.

Model statistics: <sup>1</sup>deviance = 1823.8, df = 3350, scale = 0.544; dispersion = 0.724 (0.173). <sup>2</sup>deviance = 1913.2, df = 3350, scale = 0.571; dispersion = 0.300 (0.112). <sup>3</sup>deviance = 3478.9, df = 3350, scale = 1.038; dispersion = 1.046 (0.046).

below 2.2 m, and with injury crash decrease by 3.4%, when the shoulder is over 2.2 m. The values of impact for specific crash types that were examined in the study indicate a range of 3%–6% in the first case and range of 1%–4% in the second case. In addition, an extension of the unpaved shoulder by 0.1 m is associated with injury and total crash increase by about 5%.

Concerning the impacts of other two-lane road characteristics on crashes, certain consistency was indicated across the study results. The study models showed that according to safety considerations, the preferred width of a road lane is not the widest, thus, supporting a constrained road layout as contributing to road safety, in line with modern policies of managing speeds on the secondary road network (e.g. OECD, 2006). The models indicated that a reduction in road grade may be associated with a crash reduction, as is expected in common engineering knowledge. Additionally, the results showed that providing a sufficient recovery zone on the roadside or improving barrier installation conditions (in terms of proper distances from the travel lanes and before the roadside obstacles) contribute to a reduction in the crash risk, where a recovery zone is preferable to barrier installation.

Regarding methodological considerations, similarly to previous

research (Gross and Donnell, 2011; Gross and Jovanis, 2007), the current study indicated that a case-control approach may be preferable for estimating safety effects of road design elements compared to a common multivariable modelling. The CC approach enables better treatment of the confounding factors and provides more significant results. However, a simultaneous multivariable regression modelling may be useful to verify the consistency of impacts as we learnt in this study.

The study limitations lie in the specifics of the datasets that were applied for the models' development, which reflect local Israeli conditions. The road infrastructure characteristics were produced based on video-recordings of the road network, with a consequent manual coding thus being exposed to human errors. The road section characteristics applied in this study are statistics estimated based on a range of values that might add to the uncertainty of findings. The study analyzed 1 km road units and, thus, tended to an aggregation of both crash counts and road characteristics. Similar analyses of shorter road units, e.g. of 0.5 km in length, might be useful for an additional verification of the study results.

This study examined crash data from the years 2008–2010, the time

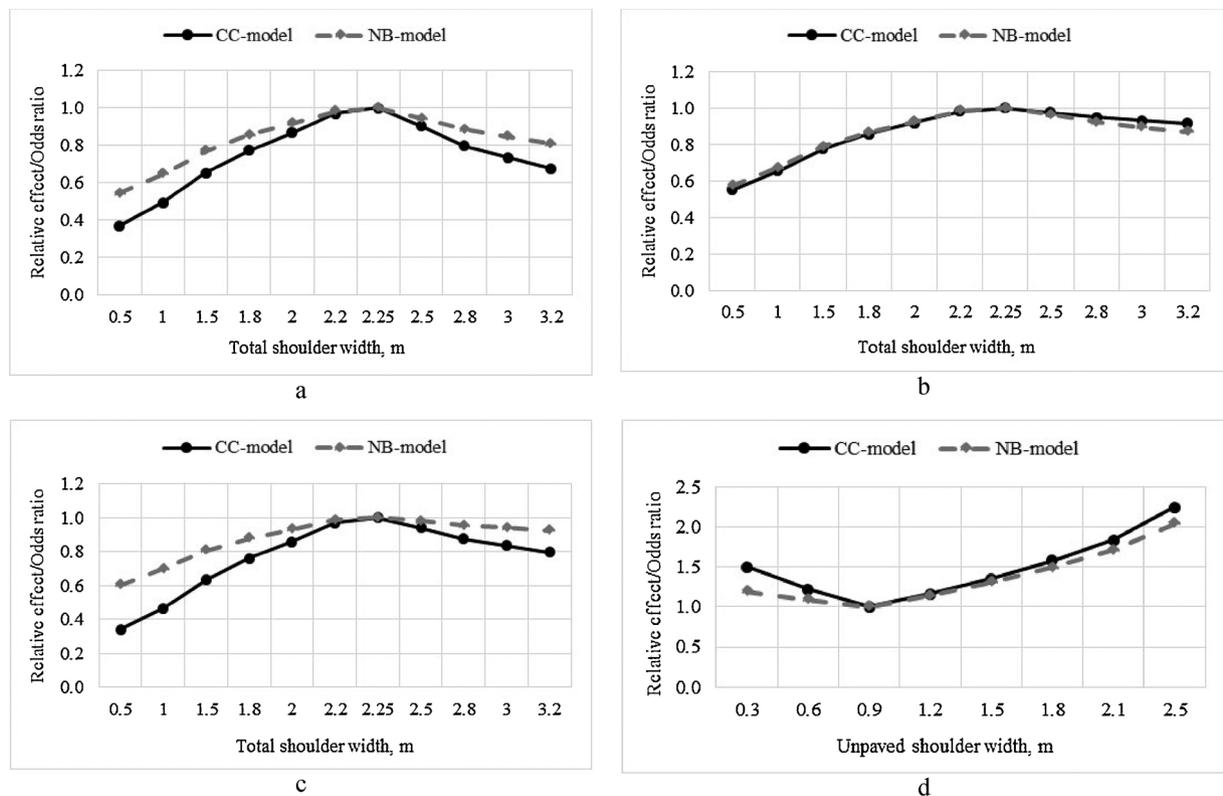


Fig. 4. Comparison of relative changes in crash risk based on CC vs NB models: (a) in single-vehicle crashes, (b) in severe crashes and (c) in total crashes, following changes in total shoulder width, and (d) in total crashes, following changes in unpaved shoulder width.

frame corresponding to road infrastructure characteristics that were collected in 2010. The Israeli non-urban road network changes rapidly due to upgrading two-lane road sections to divided roads, roadside improvements, treatments of hazardous locations, etc., whereas traffic volumes grow constantly, as well. A simple refit of crash models on later crash statistics may produce misleading results because an update of road and traffic characteristics should be performed, prior to such a re-analysis. It would be useful to repeat the analyses conducted in this study on an updated database with road infrastructure characteristics of the two-lane road network and recent crash data. More detailed information on road geometry and the presence of safety-related features (e.g. rumble strips) would be valuable in future research on the topic. Moreover, a combined consideration of road layout and roadside characteristics is needed in the future analyses, to promote the concept of self-explaining roads that is considered as contributing to creating safe traffic system (ITF, 2016).

## 6. Conclusions

The study demonstrated statistical links between shoulder characteristics and crash occurrences, on two-lane roads, under local Israeli conditions. The form of the relationship was not identical to the one that is usually referred to in the literature. However, the findings were stable across various models and crash types examined by the study, and, thus, are worth consideration. Further research of similar topics, using additional and more detailed databases with road infrastructure characteristics would be useful in the future.

The models developed in the study enable the estimation of risk change factors and crash modification factors related to changes in shoulder characteristics (width and type). These tools may assist in decision-making at the stages of design of a new road, upgrading existing road sections or treating hazardous locations. They may also support the development of a new design policy concerning preferable layouts for various road types and, particularly, the layouts intended to

attain lower target speeds on two-lane roads that were stated by recently published guidelines on managing speeds in Israel (MOT, 2010).

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