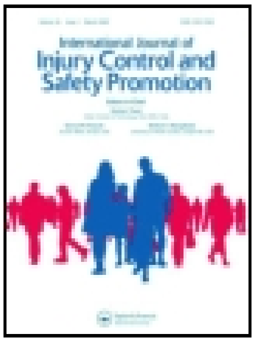

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RESEARCH ARTICLE

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Impact of Roadside Design Compliance and Hazard Offset on the Risk of Single-Vehicle, Run-Off-Road Crash Fatalities

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ABSTRACT

Single-vehicle, run-off-road (SVROR) crashes account for a significant portion of all road-related injuries and fatalities worldwide. However, no previous study has examined to what extent roadside design guidelines have been applied, nor (and most importantly) whether having a compliant roadside design reduces the likelihood of fatal injury occurrence in SVROR crashes. Thus, the objectives of this research are i) to examine the level of roadside design compliance within the studied area based on the selected benchmark and ii) to investigate whether roadside design compliance reduces the likelihood of fatal injury occurrence in SVROR crashes. Findings from this study are based on extensive crash and field data collected from 1,070 SVROR injury collisions and locations, respectively. The study shows that i) only 32 percent of the studied locations contained compliant design, and ii) barrier and discrete-obstacle lateral offsets larger than 6 and 12 meters, respectively, tended to lower fatality risk. The 12-meter clear-zone (CZ) width is larger than that recommended by previous research, which has based CZ width recommendations also on cost-benefit procedures and not just on fatality risk reduction.

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safety; run-off-road crash; roadside; design compliance; fatal injury; logistic regression

Introduction

Background

Single-vehicle run-off-road (SVROR) crashes may involve a vehicle running off the roadway and striking a fixed roadside object (e.g., tree, utility pole, traffic sign, embankment, ditch, culvert, or barrier) and/or rolling over (AASHTO, 2011). SVROR crashes account for a very significant portion of all fatal road crashes worldwide (Federal Highway Administration (FHWA), 2019; Roque et al., 2015; Somchainuck et al., 2013; Van Petegem & Wegman, 2014). For instance, in the United States, SVROR crashes accounted for 51 percent of all traffic fatalities from 2016 to 2018 (FHWA), 2019). In the Emirate of Dubai, part of the United Arab Emirates (UAE), SVROR crashes accounted for approximately 20 percent of all crash types that occurred between 1995 and 2006. Half of these crashes involved fixed-object collisions, and the other half resulted in rollovers (Al-Dah, 2010). In the Emirate of Abu Dhabi, also part of the UAE, SVROR crashes accounted for over 20 percent of all severe and fatal crashes that occurred between 2007 and 2013 (Shawky et al., 2016).

Thus, literature provides evidence that SVROR crashes have negatively impacted road user safety worldwide by contributing to a significant number of injuries and fatalities over the past many years, in spite of the fact that a number of technical manuals containing research-based design guidelines have been issued (AASHTO, 1974, 1977, 1989, 1996, AASHTO., 2002, AASHTO, 2006). This suggests that while roadside design guidelines are available, it is unknown to what extent these guidelines have been implemented and/or (most importantly) whether these guidelines have an impact on injury risk reduction. The first attempt to investigate the characteristics of installed roadside design (i.e., in terms of roadside crash locations and roadside feature configurations) dates back to the 1980s (Zeigler, 1986), which was followed by another study published in 1990 (Turner & Mansfield, 1990). However, these early studies not only were conducted a long time ago, but they were also limited to one specific roadside feature: trees.

A few past studies focused on investigating the relationship between installed urban roadside design and roadside crash frequency. These studies found that the presence of urban roadside furniture, placed to make streets more liveable, tended to significantly decrease the number of roadside crashes (Dumbaugh & Gattis, 2005; Marshall et al., 2018; Naderi, 2003). Another recent study found that streetscape design tending to result in smaller, more enclosed streetscapes contributes to both fewer injury and fatal crashes (Harvey & Aultman-Hall, 2015). Hence, these studies focused on the relationship between roadside design and crash frequency. Indeed, to date, there has been no study (to the best of our knowledge) that has investigated whether having compliant roadside design has a statistically significant impact on the reduction of fatality risk associated with SVROR collisions.

More specifically, the roadside safety and design-related literature pertaining to the Gulf Cooperation Council (GCC) region is extremely scarce. For example, the few roadside safety studies conducted in the UAE have focused on

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investigating either SVROR crash characteristics (e.g., location, object hit, and road type) or the relationship between SVROR crash frequency/severity and its contributing factors (Al-Dah, 2010; Shawky et al., 2016). That is, none of these studies examined the impact roadside design compliance has on SVROR crash severity.

Thus, a lot of research has been devoted to the development of roadside design guidelines while no effort has been undertaken (to the best of our knowledge) to examine whether compliance to these guidelines produce benefits in terms of reduced severe injury risk. For example, the minimum clear-zone (CZ) width values recommended by state-of-the-art guidelines (AASHTO, 2011) find their roots in a median-focused study conducted in rural areas during the 1960s (Hutchinson & Kennedy, 1966). This study had a number of serious limitations and was later re-examined (Cooper, 1981). Meanwhile, from the 1960s to date, vehicle fleet/technology and highway design practices have evolved, and therefore, CZ width values should be revisited. Not only that, statistical evidence that these suggested CZ width values tend to lower the risk associated with severe injuries is needed. Lastly, even though it may be intuitive to assume that the likelihood of fatal injury occurrence would be lower for locations containing compliant design, assumptions can be faulty. For example, previous research has shown that assumptions made based on results from controlled experiments, such as full-scale crash-tests, may not hold true for in-service safety evaluation studies (Albuquerque & Sicking, 2013).

In summary, while there has been a large amount of research devoted to developing roadside design guidelines (AASHTO, 2009, 2011), the extent to which existing roadside design is compliant to current state-of-the-art guidelines is unknown. Most importantly, it is unknown whether compliant roadside design does in fact reduces the likelihood of fatal injury occurrence. Hence, the objectives of this research are to i) examine the level of roadside design compliance within the studied area based on the selected benchmark and ii) to investigate whether roadside design compliance reduces the likelihood of fatal injury occurrence in SVROR crashes.

The 2012 Abu Dhabi Department of Transport (DOT) Roadside Design Guide (RDG) (Abu Dhabi Department of Transport, 2012) has been selected as the benchmark. The 2012 Abu Dhabi DOT RDG is heavily based on the 2011 American Association of State Highway and Transportation Officials (AASHTO) RDG (AASHTO, 2011). Because there may be a number of different reasons for non-compliance (e.g., inadequate CZ width, no barrier provision, or no breakaway device installed), this study also more specifically examines the impact of hazard lateral offset (HLO), traveling-lane-to-hazard lateral offset (TLHLO), and traveling-lane-to-barrier lateral offset (TLBLO) on the risk of fatal injury occurrence.

Data and methods

Study area

An assessment of the roadside design was conducted at SVROR-injury crash locations within the boundaries of the Emirate of Abu Dhabi, UAE. With an area of approximately 67,340 km^2, the Emirate of Abu Dhabi, shown in Figure 1.a (i.e., represented by the lighter-coloured area), is the largest among the seven emirates of the UAE, accounting for approximately 87 percent of the UAE's land mass (Wikipedia, 2019). Figure 1.b shows all SVROR-injury crash locations studied. As can be seen, most of the crashes studied happened in or close to the cities of Abu Dhabi and Al Ain where traffic volumes are larger.

Data collection and description

The crash databases provided by the Abu Dhabi Traffic Police were used as the crash data sources. These databases contained non-injury and injury crashes that occurred between years 2013 and 2016. Abu Dhabi Traffic Police classifies injury data as minor, moderate, severe, and fatal. Deaths occurring up to 30 days after road crashes are included in the fatal injury data. Only injury crash data contained information pertaining to the Global Positioning System (GPS) coordinates of crash locations. Thus, non-injury crash locations were not identified and, therefore, were not visited and assessed. As such, assessments conducted in this study relied on injury crash locations only.

Data were retrieved based on the number of vehicles involved and the crash type. That is, all crashes classified as having involved only one vehicle, as well as falling into the "off-road collision" category, were included in the study. This filter yielded 426 crashes. Sixteen of these crashes were excluded because they had missing GPS coordinates. Thus, 410 remaining crash locations were visited. Later on, an effort was made to ensure that no SVROR crash was left out of the study due to miscoding. As a result, a keyword (e.g., barrier, tree, pole, sign, fence, wall, and curb) search was performed within the crash description field, yielding an additional 1,081 crashes. However, due to project budget and time constraints, it was determined only 660 cases could be included in the study. These 660 crashes were selected based on random sampling which was performed using a random number generator function contained in Excel. Even though previous research found that the random number generator function in older versions of Excel presented limitations (Keeling & Pavur, 2004; MCcullough, 2008), research has also acknowledged that not only more recent versions of Excel present improvements in their random number generation capabilities (Ortiz & Deutsch, 2001; Mélard, 2014), but also that even though Excel's random number generator function is a pseudo random number generator, it is based on the Mersenne Twister algorithm (Wikipedia, 2021) which has passed several statistical tests of randomness (L'Ecuyer & Simard, 2007). This function assigned random numbers to crash cases. These crashes were then ordered based on numbers assigned to them. Finally, the first 660 out of the 1,081 cases were selected. Thus, the total number of SVROR crashes included in the study was 1,070 (i.e., 410 plus 660).

Table 1 shows how the data are broken down based on a few variables relevant to the present study. Three types of data were collected: crash, traffic, and field data. The

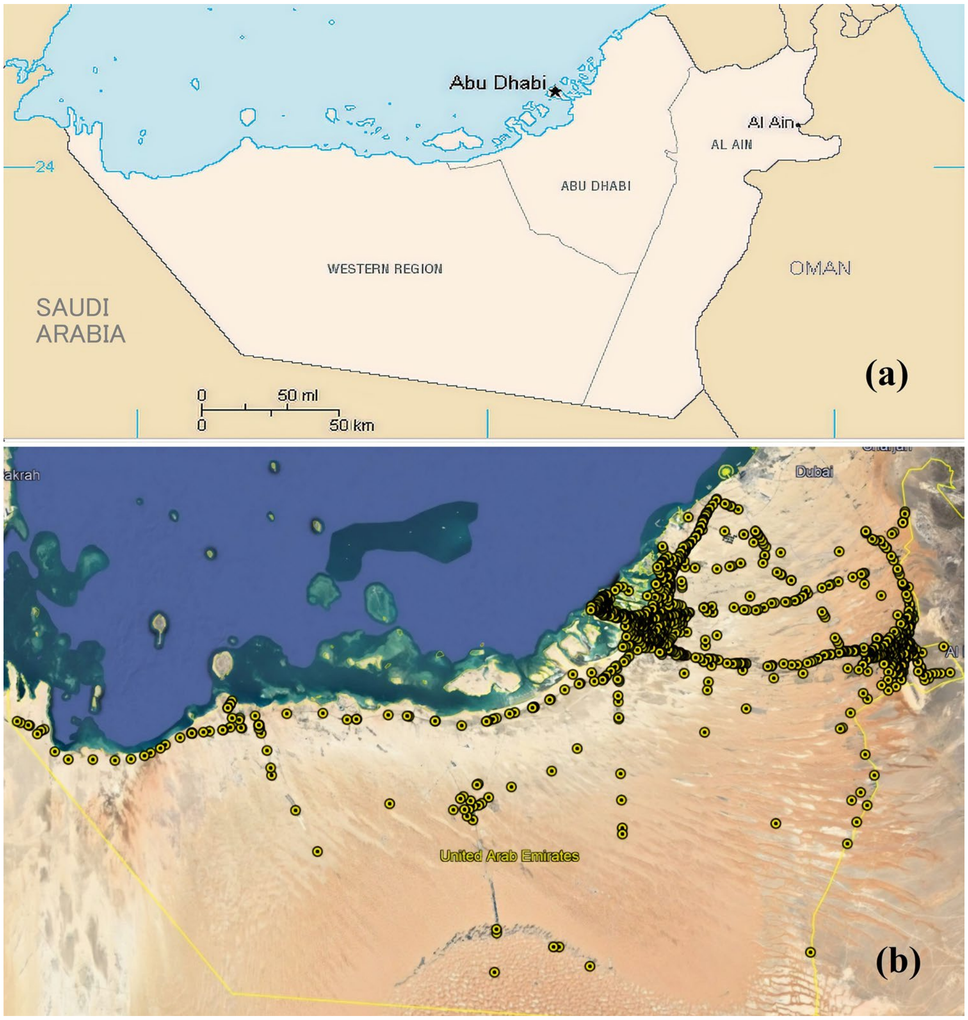


Figure 1. (a) The boundaries of the Emirate of Abu Dhabi and its three regions (Wikipedia, 2019); b) A satellite picture of the UAE: yellow dots represent the SVROR-injury crash locations studied (Google Earth, 2019).

Table 1. Data summary.

Variables	Category	Frequency	%
Most Harmful Object Struck	Tree	112	10.47
	Pole	178	16.64
	Barrier	350	32.71
	Curb	202	18.88
	Others	228	21.31
Design Speed (kph)	≤ 80	467	43.64
	≥ 100	603	56.36
Vehicle Class	Light Vehicle	992	92.71
	Heavy Vehicle	54	5.05
	Motorcycle	24	2.24
Rollover	Yes	400	37.38
	No	670	62.62
Seatbelt	Yes	701	65.51
	No	325	30.37
	Unknown	44	4.11
Crash Severity	Minor	147	13.74
	Moderate	664	62.06
	Severe	111	10.37
	Fatal	148	13.83

crash data included not only crash descriptions and diagrams, but also data on the first object struck, crash severity, and design speed. All descriptions and diagrams were reviewed in order to understand the sequence of crash events and to determine whether rollover occurred. Traffic data pertaining to the average daily traffic (ADT) at road locations of interest were obtained from the Abu Dhabi Department of Transportation (i.e., for rural highways) and municipalities (i.e., for urban facilities). Field data were collected during the 1,070 crash site visits. These data included descriptions and measurements on fixed-object type, CZ width, hazard lateral offset, curb height, barrier length, barrier-end-terminal type, hazard-to-barrier offset, roadside terrain topography, as well as breakaway device and crash cushion use/type. Finally, crash, traffic, and field data were merged into a single, injury-crash dataset.

Roadside design guidelines

The roadside design guidelines contained in the benchmark define five roadside design priorities, as illustrated by Figure 2.

Additionally, the guidelines address the items listed below.

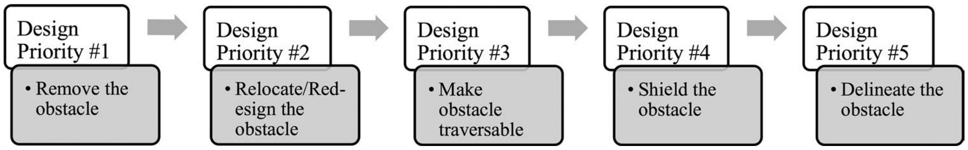


Figure 2. Roadside design priorities (AASHTO, 2011; Abu Dhabi Department of Transport, 2012).

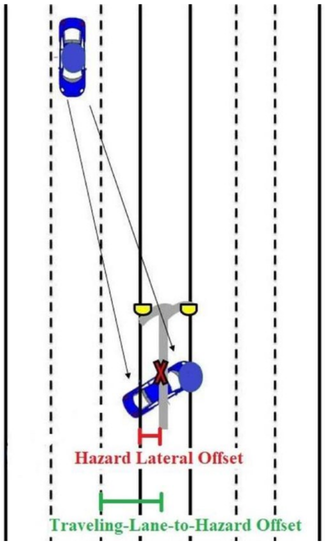
- Curb: curb heights should not exceed 15 cm and should not be installed on high-speed roads (i.e., ≥ 70 kph).
- Barrier test level (TL): barriers placed on higher-speed highways should be designed and tested to meet higher TL specifications since they will likely experience more severe collisions (AASHTO, 2009; Ross et al., 1993).
- Guardrail placement in proximity to curbs: a minimum distance of 2.5 meters between the face of the curb and the face of the barrier should be provided on roads with operating speeds of 60 kph or higher. Alternatively, guardrail face should be flush with the curb if curb height is 10 cm and operating speeds are higher than 85 kph (AASHTO, 2011; Abu Dhabi Department of Transport, 2012; Plaxico et al., 2005).
- Barrier length-of-need: the barrier length-of-need value should vary based on a set of inputs such as lateral distances from edge of travel way to back of hazard and front face of barrier, as well as barrier runout length (AASHTO, 2011; Abu Dhabi Department of Transport, 2012; Albuquerque et al., 2017).
- Barrier working-width requirements: barrier working-width refers to the lateral distance covered by the deflection of a barrier upon impact (AASHTO, 2011; Abu Dhabi Department of Transport, 2012).
- Zone-of-intrusion (ZOI) accommodation: ZOI is defined as the amount of vehicle overhang beyond the barrier during an impact. Alternatively, ZOI can be defined as the area that should be provided behind a barrier and beyond its dynamic deflection distance. ZOI values may vary widely depending on a number of variables such as barrier TL, type, and height (AASHTO, 2011; Abu Dhabi Department of Transport, 2012).

The design priorities listed in Figure 2, along with the items listed above, were taken into consideration in assessing the roadside design at crash locations.

Roadside design assessment

Table 2 provides an example of roadside design assessment performed in this study. This case pertained to a location with flat roadside terrain and ADT of over 6,000 vehicles. Design speed, roadside terrain, and ADT information are needed in order to determine the minimum recommended CZ width to be adopted (AASHTO, 2011; Abu Dhabi Department of Transport, 2012). The case shown below indicates that a light pole was located in the median within the minimum recommended CZ, but it was neither equipped with a breakaway device or any sort of energy absorbing mechanism, nor shielded by a barrier. Therefore, none of the design priorities described previously were adequately implemented in this case. Thus, this case was classified as non-compliant.

Table 2. Roadside design assessment example.

Crash description & diagram	Errant vehicle was traveling southbound in the middle lane when it left the roadway, and hit a light pole in the median.
	
Most Harmful Object Struck	Light pole
Crash Severity	Moderate
Design Speed$^{(1)}$	120 kph
Median Width	5.8 meters
CZ Width Provided and Recommended$^{(2)}$	2.25 and 12- 13 meters
Curb Height	20 cm
Breakaway Device Use	No
Barrier Use/Need/Installation Adequacy	No/ Yes /Not Applicable
Roadside Design Compliance	Non-compliant

(1) Abu Dhabi City Municipality Roadway Design Manual (Abu Dhabi City Municipality, 2014).
(2) AASHTO RDG and Abu Dhabi RDG (AASHTO, 2011; Abu Dhabi Department of Transport, 2012).

Statistical modelling

To investigate the impact of roadside design compliance on crash severity, a fitting and parsimonious regression model was used. Roadside design compliance was defined as the independent variable while crash severity the dependent or response variable. This study classifies crash severity into two levels: fatal and non-fatal. This way, crash severity miscoding issues are expected to be minimized. It is also important to note that the crash database provided by the AD Traffic Police is a crash-based, not an occupant-based dataset. As such, crash severity is classified based on the most severe injury that occurred in a crash. Nonetheless, sixty percent of all crashes included in this study involved one occupant only (i.e., the driver).

Because the response variable was coded into two different categories (i.e., fatal or non-fatal injury), a model capable of analysing categorical data was selected. Hence, the logit model was used (Agresti, 2018). The logit model has been adopted in similar road-safety-related studies in the past (Albuquerque & Awadalla, 2020a; Russo & Savolainen, 2018; Zou et al., 2014) and the fact that its outputs may be easily interpreted in terms of odds ratio was a deciding factor for using this model in this study. The binary logistic regression model can be expressed as shown in Equation 1, which gives the logit mean of the probability of the response variable as a function of a k number of explanatory variables. Taking the log of both sides will transform the function into a linear model as shown in Equation 2.

$$\text{Logit}\left[\pi(x)\right] = \text{Log}\left[\pi(x)/1-\pi(x)\right] = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_k x_k \quad (1)$$

$$\text{Odds} = e^{(\beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_n x_n)} \quad (2)$$

Thus, developing a logit model involves determining the value of the coefficients βs. The magnitude of each of these coefficients will determine the rate of change in the probability $\pi(x)$ per unit change in their respective independent variable x. The statistical method used to determine the model's parameters is the maximum likelihood estimation. A likelihood function must first be developed in order to use the maximum likelihood method. The values of the parameters that maximize the likelihood function are chosen and called the maximum likelihood estimators (Eliason, 1993). In other words, the maximum likelihood method will produce the values for the unknown parameters that maximize the probability of replicating the observed set of data. Hosmer and Lemeshow provide explanations on how the parameter values that maximize the likelihood function, in the case of a logistic regression model, are determined (Hosmer & Lemeshow, 2000). The contribution to the likelihood function for a pair of observations (x_i, y_i) may be expressed by Equation 3, which is the representation of a Bernoulli distribution since the binary logit model has only two possible outcomes. The likelihood function may be calculated by using Equation 4.

$$\varsigma(x_i) = \pi(x_i)^{y_i}\left[1-\pi(x_i)\right]^{(1-y_i)} \quad (3)$$

$$l(\beta) = \Pi_{i=1}^{n} \varsigma(x_i) \quad (4)$$

Because the observations are assumed to be independent, the contribution of n observations to the likelihood function may be expressed as the product of all $\varsigma(x)$, from observation 1 to n. The likelihood function may also be expressed in terms of summation by taking the log of $\Pi(i=1)^n$ $\varsigma(x_i)$ as shown in Equation 5, which is the log likelihood. The maximum likelihood method will find coefficients for the logit model that maximizes Equation 5. That is, the value of β that maximizes ln [l (β)] is determined. In order to determine β, ln [l (β)] is differentiated with respect to β_0 and β_1 with the resulting expressions set as equal to zero. The resulting expressions are given by Equations 6 and 7. These are the likelihood equations. Iterative methods programmed into statistical software are used to solve Equations 6 and 7 using a generalized weighted least squares procedure (McCullagh & Nelder, 1989). The solution of Equations 6 and 7 will find a value of β that is the maximum likelihood estimate.

$$\ln\left[l(\beta)\right] = \sum_{i=1}^{n}\left\{y_i \ln\left[\pi(x_i)\right] + (1-y_i)\ln\left[1-\pi(x_i)\right]\right\} \quad (5)$$

$$\sum_{i=1}^{n}\left[y_i - \pi(x_i)\right] = 0 \quad (6)$$

$$\sum_{i=1}^{n} x_i\left[y_i - \pi(x_i)\right] = 0 \quad (7)$$

Model building

Univariate analyses were first conducted to evaluate the effect of each individual predictor variable (e.g., roadside design compliance) on the response variable (i.e., crash severity). All variables shown in Table 1 were considered. All the variables that presented a p-value up to 0.25 in the univariate analysis were included in the multivariate analysis. The p-value of 0.25 was chosen as the indicator in determining which variables were to be included in the multivariate analysis and was based on recommendations made by Hosmer and Lemeshow (Hosmer & Lemeshow, 2000). The traditional p-value = 0.05 was not recommended because i) it may fail to identify variables that may be relevant to the study and ii) the univariate analysis may ignore that an isolated variable which presents a p-value larger than 0.05 may become relevant (i.e., statistically significant) when it is considered alongside other variables.

The multivariate analysis consisted of evaluating the effect of multiple predictors (e.g., most harmful object struck, design speed, rollover occurrence, and seatbelt usage) simultaneously on the response variable. Thus, multivariate analysis provides a level of control that is not provided by its univariate counterpart, allowing the effect of different independent variables on crash severity to be investigated on a fairer basis.

As multiple variables are taken together, some of them might become statistically insignificant, and each of these could then be removed from the model. This stage is called the model building stage. In this study, backward regression was used during this stage to find a final model, keeping in mind that parsimony may be particularly relevant in avoiding data sparseness.

The likelihood ratio test was used to test variable significance in the backward regression process. The likelihood ratio test compares the fit of two models by evaluating the statistical significance of the least significant variable to the model. If this variable is found to be insignificant, the simpler model is considered. The test is based on the ratio that expresses how many times more likely the data are under one model than the other. In other words, both models are fitted, and the ratio of their log-likelihood is calculated as shown in Equation 8 (i.e., deviance). The likelihood of the model is the probability that the model would be observed given the coefficient estimates.

$$D = -2\ln\left(\text{likelihood for full model} \;/\; \text{likelihood for simpler model}\right) \quad (8)$$

Goodness-of-fit test

Lastly, after a model has been selected, it is important to assess how well this model fits the data. In this study, the Hosmer-Lemeshow test was used to assess the goodness-of-fit (GOF) of the binary logit models developed (Hosmer & Lemeshow, 2000). All statistical analyses presented in this study were conducted using software Minitab 19 (Ryan et al., 2019).

Results

Assessment of roadside design compliance status (RDCS)

Out of the 1,070 crash locations studied, 728 crash locations (68.04 percent) were classified as non-compliant. As shown in Table 3, there were a number of different causes for non-compliance. Out of the 728 non-compliant locations, 471 (65 percent) were classified as non-compliant due to roadside hazards being located within the minimum recommended CZ width. Out of these 471 locations, 306 contained utility poles, traffic signs/signals, and fences not equipped with breakaway devices nor any sort of energy-absorbing mechanism (i.e., design priority 3 as shown in Figure 2). Ninety percent of all utility pole locations were classified as non-compliant due to i) poles located within the minimum recommended CZ width and either ii) no breakaway device or energy-absorbing mechanism adopted or iii) no shielding applied. Ninety percent of all tree crash locations were classified as non-compliant due to i) trees located within the minimum recommended CZ width and ii) no shielding applied. Most of the trees in the locations studied were palm trees with robust trunks of an average width of 70 cm. Fourteen percent of tree and pole crashes resulted in fatal injuries.

Moreover, 130 locations were classified as non-compliant because they either contained curbs that were too high (i.e., higher than 15 cm) or had curbs installed on high-speed roads. Twelve percent of curb crashes resulted in fatal injuries. Curb crashes were found to account for almost 19 percent of the most-often, most-harmful object struck while 47 percent of all curb crashes were followed by a rollover. About 70 percent of the curbs were found to be of a height greater than 15 cm; in contrast, benchmark guidelines recommend curbs: i) to be no higher than 15 cm on roads with design speeds of 70 kph or lower and ii) not be installed on roads with design speeds higher than 70 kph.

The remaining 127 locations were found to be non-compliant due to improper barrier usage or lack of usage. That is, 10 out of these 127 locations involved TL-2 barriers installed on high-speed roads, whereas TL-3 barriers were warranted. Twelve of these 127 locations contained guardrail installations that did not comply with the benchmark due to improper lateral offset between the barrier and curb faces. Forty-four and 13 of these 127 locations were found to be non-compliant due to insufficient ZOI and inadequate length-of-need, respectively. Finally, forty-eight of these 127 locations were non-compliant because barriers were installed but not warranted. Thirteen percent of barrier crashes resulted in fatal injuries.

Impact of RDCS on fatality risk

The upper model contained in Table 4 shows the results of the univariate analyses carried out based on variables shown in Table 1. As can be seen, there is no statistical evidence indicating that the odds of fatal crash occurrence are any different for compliant locations versus non-compliant locations (p-value = 0.75). There is also no statistical evidence showing that the odds of fatal crash occurrence are any different for light versus heavy vehicle involvement (p-value = 0.83). On the other hand, this model indicates that the odds of fatal crash occurrence are: i) 1.8 times as likely to occur on higher design-speed roads (i.e., ≥ 100 kph) as compared to lower design-speed roads (i.e., ≤ 80 kph), ii) 1.8 times as likely to occur in crashes involving rollovers as compared to crashes not involving rollovers, and iii) 2 times as likely to occur in crashes involving at least one injured occupant not wearing a seatbelt as compared to crashes in which injured occupants were wearing a seatbelt.

As all variables were taken simultaneously, all variables were found to be statistically significant at a 10-percent significance level, except RDCS and vehicle class (p-values equal to 0.24 and 0.70, respectively). Hence, the variable vehicle class was not taken into further consideration, and therefore, not included in the multivariate model shown in the bottom portion of Table 4. On the other hand, because RDCS is the main variable under investigation, it was kept in the multivariate model. The multivariate model selected shows that the odds of fatal crash occurrence are 1.3 times as likely at non-compliant locations as compared to compliant locations while controlling for design speed, rollover outcome , and seatbelt usage (i.e., p-value = 0.24). The GOF test found that the model presented an acceptable fit based on a p-value of 0.69 (i.e., higher than a critical p-value of 0.10).

As shown in Table 3, there were a number of different reasons as to why locations were classified as either compliant or non-compliant. Each one of these reasons may have had a different impact on fatality risk. Thus, it may be relevant to investigate the impact of some of these specific reasons on fatality risk. The impact of hazard shielding on the odds of fatal injury occurrence were investigated by a previously conducted study based on the same dataset used in the present study (Albuquerque & Awadalla, 2020a). The impact of HLO, TLHLO, and TLBLO on fatality risk is described in the following sections.

Impact of hazard lateral offset (HLO) on fatality risk

In order to study the impact of HLO on crash severity, HLO was classified into 3 categories: less than 6 meters (HLO < 6 m), from 6 to 12 meters (HLO = 6-12 m), and more than 12 meters (HLO > 12 m). The reasoning behind this classification is that 6 and 12 meters are the largest CZ widths recommended by the benchmark (i.e., considering that CZ width also depends on ADT and fore slope steepness) for locations with design speeds equal to 80 and 120 kph, respectively (AASHTO, 2011; Albuquerque & Awadalla, 2020b). Thus, by setting these HLO thresholds, the in-service safety performance that may result from the implementation of current state-of-the-art guidelines may be examined. Crash descriptions and diagrams, as well as views of crash locations from Google Maps, were used to measure HLO as illustrated in Table 2. Because the number of crashes that occurred at locations with HLO larger than 6 meters was a lot fewer than the number of crashes with "HLO < 6 m", only design speed was controlled for. This way, the detrimental effect of data sparseness caused by the increase in the number of independent variables was reduced. Design speed may be a reasonable surrogate measure for road classification. In the Emirate of Abu Dhabi, roads are usually represented as follows: i) local streets and collectors (design speeds up to 80 kph), ii) urban arterials (design speeds between 100 and 120 kph), and iii) rural multilane expressways (design speeds higher than 120 kph).

Table 3. Distribution of crashes by reasons for roadside design compliance and non-compliance.

Compliance	Reason	Number of Locations	Total
Yes	Hazard Outside the Minimum Recommended CZ Width	103	342 (31.96%)
	Breakaway Device Used	14	
	Hazard Shielded	225	
No	Poles/Signs Within the Minimum Recommended CZ Width, No Breakaway Device or Shielding Applied	306	728 (68.04%)
	Unshielded Trees/Walls/Others Within the CZ Width	165	
	Curb Too High or Curb Installed on High-Speed Road	130	
	Barrier Installation Related Problems	127	

The models shown in Table 5 include crashes falling into 3 different categories shown in Table 3: i) hazard outside the minimum recommended CZ width, ii) unshielded poles/signs located within the minimum recommended CZ width and not equipped with a breakaway device nor any sort of energy-absorbing mechanism, and iii) unshielded trees/walls/others located within the minimum recommended CZ width. The first model included all SVROR-injury crashes, the second model excluded free-collision events, and the last model excluded not only free-collision events but also curb crashes. The findings from a previous study, based on the same dataset used in the present research, found that collision-free events and curb crashes tend to be less severe than tree/pole/barrier crashes (Albuquerque & Awadalla, 2020a). Thus, excluding collision-free events and curb crashes is

Table 4. Impact of RDCS on fatality risk: univariate and multivariate models.

Variable	Non-Baseline Category	Baseline Category	Total # Observations	# Non-Baseline Observations	Odds Ratio	P-value	GOF (p-value)
RDCS	No	Yes	1,070	342	1.1	0.75	NA
Design Speed	≥ 100 kph	≤ 80 kph	1,070	603	1.8	0.00	
Rollover Occurrence	Yes	No	1,070	400	1.8	0.00	
Seatbelt Usage	No	Yes	1,026	325	2.0	0.00	
Vehicle Class	Light Vehicle	Heavy Vehicle	1,046	992	1.1	0.83	
RDCS	No	Yes	1,026	705	1.3	0.24	0.69
Design Speed	≥ 100 kph	≤ 80 kph		575	1.8	0.01	
Rollover Occurrence	Yes	No		380	1.6	0.02	
Seatbelt Usage	No	Yes		325	1.9	0.00	

Table 5. Impact of HLO on fatality risk.

SVROR Crash Type	Variable	Non-Baseline Category	Baseline Category	Total # Observations	# Non-Baseline Observations	Odds Ratio	P-value	GOF (p-value)
All SVROR	HLO	< 6	> 12	574	451	1.5	0.32	0.48
		6.0 – 12.0			59	2.3	0.09	
	Design Speed	≥ 100 kph	≤ 80 kph		241	2.5	0.00	
No Collision-Free Events	HLO	< 6	> 12	516	443	5.2	0.11	0.27
		6.0 – 12.0			49	9.9	0.03	
	Design Speed	≥ 100 kph	≤ 80 kph		195	2.7	0.00	
No Collision-Free Events or Curb Crashes	HLO	< 6	> 12	383	316	4.9	0.13	0.20
		6.0 – 12.0			45	9.7	0.04	
	Design Speed	≥ 100 kph	≤ 80 kph		164	2.7	0.00	

important in order to more accurately quantify the impact that HLO may have on crash severity. Furthermore, barrier crashes were also excluded from the data used in the models shown in Table 5, as previous research using the same dataset used in the present research showed that w-guardrail crashes are less severe than tree/pole crashes (Albuquerque & Awadalla, 2020a). This is also relevant because CZ width policy aims at addressing locations with hazards such as trees and poles instead of barriers. The effect of barrier lateral offset on the risk of fatality associated with barrier crash is examined later in this paper.

The first model shown in Table 5 indicates that the odds of fatal crash occurrence are 1.5 times as likely at locations with “HLO < 6 m” as compared to locations with “HLO > 12 m” (p-value = 0.32), whereas the odds of fatal crash occurrence are 2.3 times as likely at locations with “HLO = 6-12 m” as compared to locations with “HLO > 12 m” (p-value = 0.09). The second model indicates that the odds of fatal crash occurrence are 5.2 as likely at locations with “HLO < 6 m” as compared to locations with “HLO > 12 m” (p-value = 0.11), whereas the odds of fatal crash occurrence are 9.9 as likely at locations with “HLO = 6-12 m” as compared to those with “HLO > 12 m” (p-value = 0.03). Thus, when collision-free events are excluded, the impact of HLO on fatality risk is more pronounced as the odds are increased. Similar results were found by the third model listed in Table 5, which excluded not only collision-free events but also curb crashes. These three models also indicate (though not shown in Table 5) that the odds of fatal injuries occurrence were 1.5 (p-value = 0.25), 1.9 (p-value = 0.08), and 2.0 (p-value = 0.08) times higher for crashes occurring at locations with “HLO = 6-12 m” as compared to those with “HLO < 6 m”, which may be considered a counterintuitive finding. These results may have been influenced by the fact that different types of objects struck most often occur within specific offset ranges. That is, lateral offset cumulative distributions by type of object struck revealed that trees tended to be farther away from the roadway edge than other obstacles, making them more likely to fall into the “HLO = 6-12 m” range. Almost all trees struck were palm trees with an average width of 70 cm.

Impact of traveling-lane-to-hazard lateral offset (TLHLO) on fatality risk

Further analysis was conducted by replacing the HLO with TLHLO, as indicated in the figure in Table 2. By using TLHLO, the focus was shifted from merely recording the distance of the roadway edge to the hazard to instead taking into account the lane in which the vehicle actually became out of control to the point that it hit the hazard. Results from this analysis are shown in Table 6. As can be seen, the first model shown in Table 6 indicates that fatal injuries are almost 1.5 times as likely to occur at locations with “TLHLO < 6 m” as compared to those with “TLHLO > 12 m”, as well as 1.6 times as likely to occur at locations with “TLHLO = 6-12 m” as compared to those with “TLHLO > 12 m”. However, both of these findings were not found to be statistically significant based on p-values of 0.45 and 0.37, respectively.

Impact of traveling-lane-to-barrier-lateral offset (TLBLO) on fatality risk

In this section, the impact of traveling-lane-to-barrier-lateral offset (TLBLO) on fatality risk is examined. The largest barrier lateral offset (BLO) was 7 meters. Thus, by focusing on TLBLO instead of BLO, the effect of wider distances (i.e., larger than 7 meters) between barriers and traveling vehicles may be examined. It was not possible to identify the traveling lane for 10 barrier crashes. Thus, the resulting number of barrier crashes used was 340.

Table 7 shows that the odds of fatal crash occurrence are 1.5 times as likely at locations with “TLBLO < 6 m” as compared to those with “TLBLO > 6 m” (p-value = 0.19).

Discussion

There was no statistical evidence (p-value = 0.24) found that roadside design compliance tends to reduce fatality risk, while controlling for design speed, rollover outcome, and seatbelt usage (see Table 4). However, in order to better investigate the effect of roadside design compliance on fatality risk, data were stratified by compliance/non-compliance reasons and type of object struck. As a result, the effect of different CZ width ranges on fatality risk, while controlling for type of

Table 6. Impact of TLHLO on fatality risk.

Crash Type	Variable	Non-Baseline Category	Baseline Category	Total # Observations	# Non-Baseline Observations	Odds Ratio	P-value	GOF (p-value)
No Collision-Free Events or Curb Crashes	TLHLO	< 6	> 12		206	1.5	0.45	
		6.0 – 12.0			124	1.6	0.33	
	Design Speed	≥ 100 kph	≤ 80 kph	376	163	2.6	0.00	0.50

Table 7. Impact of TLBLO on fatality risk.

Variable	Non-Baseline Category	Baseline Category	Total # Observations	# Non-Baseline Observations	Odds Ratio	P-value	GOF (p-value)
TLBLO	<6	≥ 6		175	1.5	0.19	
Design Speed	≥ 100 kph	≤ 80 kph	340	291	1.6	0.35	0.93

object struck, was studied (see Tables 5–7). Model in Table 5 suggests that hazard offsets of 12 meters or larger are likely to reduce fatality risk. The 12-meter CZ width is larger than that recommended by previous research. However, previous research has based its recommendations also on cost-benefit procedures and not only on fatality risk reduction (Graham & Hardwood, 1982). Another previous study found that the provision of a 6-meter "safety zone" did not significantly reduce crash severity (Missouri State Highway Commission, Unpublished memorandum). In this previously conducted study, "safety zone" was defined as an obstacle-free area extending 6 meters beyond the shoulder.

The large differences between the odds shown in Tables 5 and 6 (i.e., 4.9 and 9.7 versus 1.5 and 1.6, respectively) may be attributed to the fact that as the definitions of HLO and TLHLO differ, some of the crash cases moved across different offset categories as analysis moved from being HLO- to TLHLO-based. The fact that the number of crash cases in categories with larger lateral offsets (i.e., "= 6-12 m" or "> 12 m") increased considerably (as analysis moved from being HLO- to TLHLO-based) means that many vehicles were traveling in lanes farther from the roadside and closer to the median (if any). Considering that: i) the distance from road edge to hazard is the same irrespective of whether HLO or TLHLO is used, and ii) no statistical evidence was found showing that locations with larger TLHLOs were associated with lower fatality risk, it may mean that hazards should be placed as far away from the road edge as possible no matter what the number of road lanes is. This is in line with state-of-the-art guidelines (AASHTO, 2011; Abu Dhabi Department of Transport, 2012) which do not base CZ width values on the number of road lanes.

Table 7 suggests that the odds of fatal crash occurrence are reduced if barriers are installed with offsets no less than 6 meters from the roadway edge. Obviously, since barriers must be installed to shield, and therefore to be in front of a hazard that cannot be removed, redesigned, or relocated, barriers are often installed with offsets shorter than 6 meters. Nevertheless, this study suggests that designers must strive for wider barrier lateral offsets wherever possible.

A number of p-values shown in Tables 4–7 are higher than 0.10 (i.e., commonly used threshold for statistical significance). However, Ezra Hauer points to the problem of possible misinterpretation of data associated with the application of significance testing (Hauer, 2004). That is, because a model parameter is not statistically significant (e.g., at a 10 percent level), this does not mean the effect of the variable associated with that parameter on the dependent variable is zero. That is, Ezra Hauer argues that the parameter value provides information on the most likely effect that predictor variable has on the response variable, and therefore, may still provide relevant information in regards to the most likely direction of that effect. Finally, paying more attention to the most likely effect that a predictor variable has on the response variable rather than focusing exclusively on statistical significance may be overlooked by the fact that statistical significance might be reached by increasing sample size.

It is also important to highlight that crash underreporting may have had an effect on the magnitude of the odds reported in this study. That is, since underreporting is more recurrent among lower-severity crashes and crash severity may tend to be lower at compliant locations as well as at locations with wider hazard/barrier offsets, it may be reasonable to assume that underreporting may be more prevalent among crashes that occurred at compliant locations and locations with wider hazard/barrier offsets. If this is the case, then the actual odds should be higher than those reported. Hence, the safety benefits associated with roadside design compliance and wider hazard/barrier offsets may be underestimated if the estimated odds presented in the current study are not adjusted for underreporting. Thus, the need for taking underreporting into account is relevant, as the findings from this study may be helpful in the development of severity indices and in the evaluation of proposed roadside safety improvements.

Conclusions

The majority of the crash locations studied contained non-compliant roadside design. This suggests that, while state-of-the-art roadside design guidelines have been available for several years now, their availability has not translated into proper roadside design installation. The main reasons for non-compliance were: i) CZ width narrower than the minimum recommended, ii) barrier misplacement, barrier layout related deficiencies, or inadequate barrier TL, and iii) excessive curb height or curb installation on high-speed roads. Most importantly, it was found that non-compliant design is more likely to increase fatality risk, though a larger sample size may be required to make this finding to be statistically significant.

The present study supports the adoption of CZ widths larger than 12 meters (as a means to reduce fatality risk), as recommended by state-of-the-art guidelines (AASHTO, 2011; Abu Dhabi Department of Transport, 2012). On the other hand, state-of-the-art guidelines also provide recommendations for CZ width ranges less than 6 meters as well as between 6 and 12 meters, depending on design speed, traffic volume, and terrain topography values; however, the present study found no consistency in relation to differences in fatality risk between these CZ width ranges. The findings from the present study are based exclusively on fatality risk, while state-of-the-art guidelines are based on cost-effectiveness as well. Furthermore, the present study found that fatality risk was not impacted by TLHLO. Thus, hazards should be placed as far away from the road edge as possible, no matter the number of road lanes. This is also in line with state-of-the-art guidelines (AASHTO, 2011; Abu Dhabi Department of Transport, 2012) which do not base CZ width values on the number of road lanes. Lastly, barrier offset larger than 6 meters was also found to be more likely to reduce fatality risk.

In light of the potential difficulty in providing such large hazard and barrier offsets, designers are encouraged to remove/redesign obstacles wherever possible. Alternatively, posted speed limits can be reduced on roads where capacity constrain is not a concern. This study found that higher design speeds were found to significantly increase fatality risk.

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