Article

Identification of Risk Factors Associated with Fatal Intersection Crashes and Assessment of the In-Service Safety Performance of Signalized Intersections and Roundabouts in Abu Dhabi

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Abstract: Several research studies conducted in North America and Europe have consistently shown that converting signalized intersections into roundabouts leads to safety benefits. These studies have led North American and European transportation agencies to convert hundreds of signalized intersections into roundabouts over the last few decades. Meanwhile, the Emirate of Abu Dhabi, the largest emirate in the United Arab Emirates (UAE), has replaced many of its long-standing roundabouts with signalized intersections (i.e., controlled by traffic lights) despite the fact that no UAE-based scientific study comparing the safety performance of these two intersection types can be found in the literature. Hence, the objectives of this paper are to (i) identify factors that significantly contribute to fatal intersection-related crashes and (ii) assess the in-service safety performance of signalized intersections and roundabouts. It is anticipated that the findings from this research will provide road designers and decision-makers with much needed scientific guidance on which factors contribute to fatal intersection crashes as well as on whether converting existing roundabouts into signalized intersections improves public safety or not in Abu Dhabi. The findings from this research should also benefit neighboring Gulf Cooperation Council (GCC) countries considering their similarities in road design, traffic characteristics, and driving culture.

Keywords: traffic safety; intersection crashes; injuries; logistic regression; Abu Dhabi

1. Introduction

1.1. Background

Traffic-related injuries and deaths have been a significant public health problem not only in the United Arab Emirates (UAE) [1–3], but also in other Gulf Cooperation Council (GCC) countries (i.e., Bahrain, Kuwait, Oman, Qatar, and Saudi Arabia) [4–9]. More specifically, intersection crashes account for a disproportional number of traffic-related injuries and deaths in Abu Dhabi [10]. In fact, intersection crashes have accounted for a significant portion of all road-related crashes and severe injuries worldwide. For instance, intersection crashes have accounted for one-quarter and one-half of all traffic-related fatalities and injuries, respectively, in the United States (US) [11]. Thus, considering that the World Health Organization (WHO) has defined road crashes as a serious public health problem [12], and given the significant number of traffic-related crashes and deaths occurring at intersections, it is imperative that both the number and (most importantly) the severity of crashes occurring at intersections be reduced if road safety is to be improved.

In Abu Dhabi city, running-red-light crashes alone have been found to account for almost one-fifth of all traffic-related fatalities. Eighty-five percent of these crashes involved right-angle impacts, while the number of injuries and vehicles involved in these crashes were found to be 27 and 32%, respectively, higher as compared to those from all crash

types combined [10]. Roundabouts may be a design alternative with the potential to improve safety in Abu Dhabi intersections. Roundabouts may improve safety by lowering traveling speeds due to the presence of the center island and curved approaches. In addition, circular movements and angled entry trajectories decrease the chance of more severe impact conditions such as those involved in right-angle collisions [13–60].

Indeed, scientific research has found that the adoption of roundabouts should be favored over signalized intersections (i.e., controlled by traffic lights) if safety is to be improved. However, the Emirate of Abu Dhabi has so far converted several of its long-standing roundabouts into signalized intersections [61,62]. This is puzzling, as a significant amount of research has shown that this move may pose a mobility safety threat to the motoring public in the UAE. For example, research conducted in the 2000s reported a meta-analysis of several studies [13–50] conducted between 1975 and 1997 outside the US (see Table 1) [63]. These studies used two different study designs: before-after (most of them) and cross-sectional. Unfortunately, many of these studies did not control for the regression-to-the-mean (RTM) phenomenon [64]. The findings from this comprehensive, meta-analysis-based study revealed that roundabouts are associated with a 30 to 50% reduction in the number of injury accidents, while fatal accidents are reduced by 50 to 70%.

Table 1. List of Studies [13–50] Included in the Meta-Analysis-Based Research Conducted by Elvik (2003) [63].

Year	Authors	Country	Design	Controls for RTM	Number of Estimates of Effect
1975	Lalani	Great Britain	Before-after	No	2
1977	Green	Great Britain	Before-after	No	8
1981	Lahrmann	Denmark	Both designs	No	4
1983	Cedersund	Sweden	Cross-section	Not relevant	20
1983	Senneset	Norway	Before-after	No	1
1985	Brüde and Larsson	Sweden	Before-after	Yes	1
1985	Johannessen	Norway	Cross-section	Not relevant	2
1988	Hall and McDonald	Great Britain	Cross-section	Not relevant	4
1988	Nygaard	Norway	Before-after	No	1
1990	Giaever	Norway	Cross-section	Not relevant	3
1990	Van Minnen	Netherlands	Before-after	No	4
1991	Jørgensen	Denmark	Before-after	No	3
1992	Brüde and Larsson	Sweden	Cross-section	Not relevant	12
1992	Dagersten	Switzerland	Before-after	No	2
1992	Holzwarth	Germany	Before-after	No	2
1992	Hydén et al.	Sweden	Before-after	No	8
1992	Johannessen	Denmark	Before-after	No	2
1992	Kristiansen	Norway	Before-after	No	4
1992	Schnüll et al.	Germany	Before-after	No	2
1992	Værø	Denmark	Before-after	No	2
1993	Brilon et al.	Germany	Before-after	No	2
1993	Schoon and Van Minnen	Netherlands	Before-after	No	9
1994	Voss	Germany	Cross-section	Not relevant	4
1994	Jørgensen	Denmark	Before-after	Yes	1
1994	Seim	Norway	Before-after	No	3
1994	Huber and Bühlmann	Switzerland	Before-after	No	2
1995	Oslo Veivesen	Norway	Before-after	No	1
1996	Odberg	Norway	Before-after	Yes	2
1997	Giaever	Norway	Before-after	No	2

More recently, a meta-analysis study investigated the road safety effects of converting junctions into roundabouts [65]. The objective of this study was to update the meta-analysis study conducted in the 2000s [63], as the data used in this older study was not only outdated, but it also focused on non-US studies. A total of 44 studies (i.e., the 33 studies [13–50] shown in Table 1 plus the 11 studies [51–60] shown in Table 2) were included in this meta-analysis-based research, including studies conducted in Norway, Denmark, Great Britain, Sweden, Germany, Switzerland, the Netherlands, Belgium, Australia, and the US. These studies were conducted between 1975 and 2014. Based on a total of 154 estimates of effect, this more recent meta-analysis research [65] showed that converting junctions into roundabouts was associated with a reduction in fatal accidents of about 65% and a reduction in injury accidents of about 40%. Based on these results, this comprehensive research concluded that roundabouts are very effective in reducing traffic fatalities. Other recent research has confirmed findings from this meta-analysis study [66].

Table 2. List of Studies [13–60] Included in the Meta-Analysis-Based Research Conducted by Elvik (2017) [65].

Year	Authors	Country	Design	Controls for RTM	Number of Estimates of Effect
1990	Corben et al.	Australia	Before-after	No	1
1990	Tudge	Australia	Before-after	No	3
1995	Bureau of Transport and Communications Economics	Australia	Before-after	No	2
1996	Flannery and Datta	United States	Before-after	Yes	2
1998	Flannery et al.	United States	Before-after	No	2
1998	Mountain et al.	Great Britain	Before-after	Yes	2
2001	Newstead and Corben	Australia	Before-after	Yes	1
2001	Persaud et al.	United States	Before-after	Yes	7
2007	Brabander and Vereeck	Belgium	Before-after	Yes	4
2008	Meuleners et al.	Australia	Before-after	No	2
2009	Schelling and Jerpersen	Denmark	Before-after	Yes	1
2013	Gross et al.	United States	Before-after	Yes	4
2013	Underlien Jensen	Denmark	Before-after	Yes	4
2014	De Pauw et al.	Belgium	Before-after	Yes	2
2014	Hu et al.	United States	Before-after	No	4

Even though there has been a significant amount of studies conducted at different points in time and spread throughout several different countries and continents, assessing the safety performance of roundabouts versus signalized intersections in the Emirate of Abu Dhabi is still a relevant research topic, since (i) there has been no scientific evaluation of the in-service safety performance of roundabouts and signalized intersections in the UAE, and (ii) traffic characteristics, vehicle fleet, and driving behavior in the UAE may differ from those in the countries listed in Tables 1 and 2. For example, a recent study conducted using Abu Dhabi crash data found that half of the road crashes were caused by reckless behavior and that Emirati drivers were very overrepresented as the driver at fault in fatal crashes [67]. One of the practices classified as reckless in this study was "no yielding" when yielding was warranted, such as when vehicles are entering roundabouts. Another recent Abu Dhabi study found that the 85th percentile operating speeds from a sample of 18 roundabouts in Abu Dhabi were found to be higher than the design speeds and that motorists perceive roundabouts as unsafe [68]. As such, given the reckless driving behavior tendencies present among Abu Dhabi motorists and the fact that motorists traveling through roundabouts may have more control over factors such as yielding, driving speeds, and gap acceptance as opposed to traveling through signalized intersections, roundabout safety in Abu Dhabi

may be negatively affected. This potentially reduced roundabout safety could then make roundabouts in Abu Dhabi not as safe as those in North American and European countries.

Thus, there is a need for an evaluation of the in-service safety performance of roundabouts and signalized intersections in the Emirate of Abu Dhabi, especially given that several of its long-standing roundabouts have been (and may continue to be) replaced with signalized intersections.
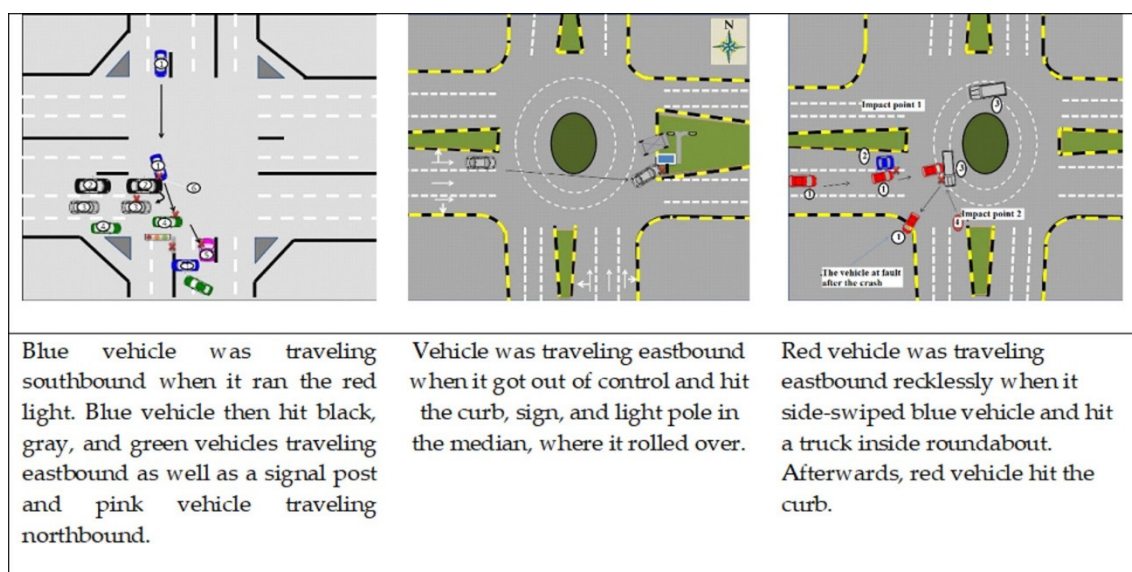
1.2. Research Objectives

This research aims at answering the following questions:

(i) Which crash-, road-, traffic-, intersection-, vehicle-, and driver-related characteristics significantly contribute to more fatal signalized intersection- and roundabout-related crashes?

(ii) Which intersection type presents a higher likelihood for fatal crashes to occur?

2. Methods

2.1. Data Collection and Description

A multi-year crash database, provided by the Abu Dhabi Traffic Police, was used to study signalized intersection and roundabout injury crashes between 2012 and 2017 in the Emirate of Abu Dhabi, part of the UAE. The Emirate of Abu Dhabi is the largest of the UAE's seven emirates, occupying about 85% of the country's landmass. Only injury crashes contained location information and, therefore, it was not possible to identify intersection type for non-injury data. In addition, non-injury data did not contain detailed crash descriptions or crash diagrams. As a result, non-injury data was not included in the study. The 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. Intersection crashes were retrieved using keyword (i.e., roundabout, signal, and intersection) search within the crash description and location fields. A total of 2147 intersection injury crashes were identified. Crash descriptions and diagrams of these crashes were manually reviewed in order to ensure that crashes occurred within intersection boundaries. This exercise led to the exclusion of 139 crashes (i.e., since they had actually not occurred within an intersection), resulting in a total of 2008 crashes (i.e., 794 roundabout and 1214 signalized intersection crashes). There was no field in the databases for information on the sequence of events, rollover outcome, and intersection type. Thus, all crash descriptions and diagrams had to be manually reviewed to identify intersection type, sequence of crash events, and rollover occurrence outcome. Figure 1 shows examples of crash descriptions and diagrams for some of the studied intersection cases. Table 3 shows all variables included in the study. All crash locations were reviewed on Google Earth in order to collect data on intersection features: roundabout island diameter, number of lanes inside the roundabout, signalized intersection area, presence of left or right turn lanes, curvature of the roundabout entry approach, median width, width of entry approach, presence of access points on the upstream approach, number of intersection approach lanes, crosswalk presence, distance between crosswalk and the roundabout yielding line, presence and length of separate left-turn lanes, presence and length of separate right-turn lanes, number of left and right turn lanes, and number of through lanes (i.e., at signalized intersections).

Blue vehicle was traveling southbound when it ran the red light. Blue vehicle then hit black, gray, and green vehicles traveling eastbound as well as a signal post and pink vehicle traveling northbound.	Vehicle was traveling eastbound when it got out of control and hit the curb, sign, and light pole in the median, where it rolled over.	Red vehicle was traveling eastbound recklessly when it side-swiped blue vehicle and hit a truck inside roundabout. Afterwards, red vehicle hit the curb.

Figure 1. Crash Descriptions and Diagrams.

Table 3. Intersection Crash Data Summary.

Variable	Categories	Frequency	%
Presence of Access Points	No	421	21.0
	Yes	1441	71.8
	Unknown	146	7.3
Number of Crash Events	One	1253	62.4
	Multiple	755	37.6
Number of Vehicles Involved	One	732	36.5
	Multiple	1276	63.5
Number of Intersection Approach Lanes	3 or less	841	41.9
	4 or more	1019	50.7
	Unknown	148	7.4
Number of Intersection Arms	3 or less	517	25.7
	4 or more	1491	74.3
Driver Age	Continuous	1989	99.1
	Unknown	19	0.9
Driver Nationality	Emirati	595	29.6
	Others	1405	70.0
	Unknown	8	0.4
Driver Gender	Male	1709	85.1
	Female	291	14.5
	Unknown	8	0.4
Crash Type	Angled	877	43.7
	Run-of-Road	512	25.5
	Rear-End/Head-On	387	19.3
	Others	232	11.6
Distance Between Signalized Intersections	≤500 km	378	31.1
	>500 km	762	62.8
	No Intersection/Unknown	74	6.1
Distance Between Roundabout and Nearest Intersection	≤1 km	281	35.4
	>1 km	300	37.8
	No Intersection/Unknown	213	26.8

Table 3. *Cont.*

Variable	Categories	Frequency	%
Land Use	Urban	1835	91.4
	Rural	173	8.6
Presence of Separate Left-Turn Lane	No Lanes	945	51.7
	Single Lane	584	47.2
	Multiple Lanes	450	1.0
	Unknown	29	1.0
Length of Left-Turn Lane	Continuous	1973	98.3
	Unknown	35	1.7
Road Light Condition	Good	1958	97.5
	Poor or No Light	50	2.5
Median Width	≤5 m	441	22.0
	5 to 10 m	886	44.1
	>10	502	25.0
	Unknown	179	8.9
Object Struck	Vehicle	1237	61.6
	Roadside Hazard	513	25.5
	Nothing	59	2.9
	Others	199	9.9
Driver Physical Condition	Impaired	107	5.3
	Not Impaired	1128	56.2
	Unknown	773	38.5
Presence of Pedestrian Crosswalk	Yes	1376	68.5
	No	579	28.8
	Unknown	53	2.6
Weather	Not Adverse	1953	97.3
	Adverse	44	2.2
	Unknown	11	0.5
Posted Speed Limit (kph)	≤60	1536	76.5
	≥80	472	23.5
Vehicle Class	Light Vehicle	1750	87.2
	Heavy Vehicle	182	9.1
	Others	76	3.8
Rollover	Yes	265	13.2
	No	1743	86.8
Seatbelt Use	Yes	1054	52.5
	No	720	35.9
	Unknown	210	10.5
Crash Severity	Fatal	101	5.0
	Not Fatal	1907	95.0

2.2. Statistical Modeling

Multivariate logistic regression models were used to:

(i) identify risk factors to fatal intersection crashes while controlling for potential crash severity contributing factors. These models aimed at addressing the first objective of this study (i.e., as stated in Section 1.2). In these models, crash-, road-, traffic-, intersection-, vehicle-, and driver-related factors were defined as independent variables, while crash severity was defined as the dependent or response variable.

(ii) quantify the odds of incurring fatal injuries given that collisions at different intersection types have occurred while also controlling for potential crash severity contributing factors. These models aimed at addressing the second objective of this study (i.e., as also stated in Section 1.2). In these models, intersection type was defined

as the independent variable, while crash severity was defined as the dependent or response variable.

A univariate logit model may be mathematically expressed by Equation (1), where x is the predictor variable (e.g., intersection type), $\pi(x)$ is the success (defined as fatal injury) probability at the value x, β_0 is the intercept, and β represents the effect of the variable x on the response variable.

$$\text{Logit } [\pi(x)] = \beta_0 + \beta x, \tag{1}$$

A multivariate logit model with n predictor variables may be expressed by Equation (2). In order to calculate the odds estimate, the exponential of the logit is determined by Equation (3). Since the response variable is binary (i.e., y = non-fatal or fatal injury), a binary logit model was used. The binary logit model calculates the probability that the response, coded as y equal to 0 or 1, is equal to 1 (e.g., π [y = fatal crash]), which would mean "success". Therefore, logistic regression models can help quantify the odds associated with a fatal crash occurrence upon a collision with different intersection types while controlling for a number of relevant vehicle-, road-, and occupant-related variables (i.e., potential crash severity contributing factors).

$$\text{Logit } [\pi(x)] = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_n x_n, \tag{2}$$

$$\text{Odds} = e^{(\beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_n x_n)} \tag{3}$$

In order to fit the logistic regression model, the coefficient(s) beta(s) need to be determined. The statistical method used to determine the model's parameters is the maximum likelihood estimation [69]. 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 [70]. Iterative methods programmed into statistical software are used to solve likelihood equations using a generalized weighted least squares procedure [71] and find a value of β that is the maximum likelihood estimate. All statistical analyses presented in this study were conducted using software Minitab 19 [72]. Model building procedures as well as goodness-of-fit test used during the development of the models contained in this study have been detailed in a recently published paper [73]. Therefore, interested readers are referred to this previously published paper, as the same procedures applied in that paper were applied to the current one.

3. Results

A total of 2008 intersection crashes were studied. These crashes occurred in the Emirate of Abu Dhabi between years 2012 and 2017. Out of these, 1214 (60.45%) crashes occurred at signalized intersections, while 794 (39.55%) crashes occurred at roundabouts. Seven percent of the roundabout crashes resulted in fatalities, while 3.7% of the signalized intersections resulted in fatalities.

Three different multivariate models were developed in this study. One multivariate model was developed to identify risk factors associated with fatal signalized intersection crashes (see Section 3.1), another multivariate model was developed to identify risk factors associated with fatal roundabout crashes (see Section 3.2), and one final multivariate model was developed to compare the in-service safety performances of signalized intersections to that of roundabouts (see Section 3.3).

3.1. Risk Factors Associated with Fatal Signalized Intersection Crashes

A univariate analysis was first performed using crash severity as the dependent variable and the other variables listed in Table 3 as the independent variables. Table 4 shows the results from the univariate analysis. Driver's age, distance between intersections, number of crash events, presence of the access points on the upstream intersection approach, presence of left-turn lanes, number of lanes in the intersection approach (i.e., where the vehicle at fault came from), vehicle class, number of intersection arms, number of vehicles

involved, posted speed limit, and seatbelt usage were all considered in the multivariate analysis (i.e., based on a *p*-value of 0.25 or below). As mentioned in Section 2.2, details on why a *p*-value of 0.25 is used to consider variables further into a multivariate analysis can be found in a recently published study [73].

Table 4. Univariate Analysis: Signalized Intersections.

Variable	Non-Baseline Category	Baseline Category	Total # Observations	# Non-Baseline Observations	Odds	*p*-Value	ANOVA *p*-Value
Driver Age	-	-	1208	-	0.98	0.25	0.25
Distance Between Signalized Intersections	>500 m	≤500 m	1140	762	1.7	0.14	0.14
Number of Crash Events	Multiple	One	1214	333	1.4	0.25	0.25
Presence of Access Points	No	Yes	1179	182	1.6	0.20	0.20
Presence of Separate Left-Turn Lanes	No lanes Single Lane	Multiple Lanes	1185	151 584	1.1 2.2	0.9 0.0	0.07
Number of Intersection Approach Lanes	≤ 4	≥ 5	1179	577	1.6	0.13	0.13
Vehicle Class	Heavy Vehicle	Light Vehicle	1174	87	2.4	0.05	0.05
Number of Intersection Arms	3	4	1209	241	1.5	0.25	0.25
Number of Vehicles Involved	One	Multiple	1214	166	3.61	0.00	0.00
Posted Speed Limit (kph)	≥ 80	≤ 60	1214	263	1.61	0.14	0.14
Seatbelt Usage	No	Yes	1004	385	4.41	0.00	0.00

As can be seen, fatal injuries are 1.7 times more likely to occur (as compared to non-fatal injuries) at locations where intersections are separated by a distance of more than 500 m as compared to locations where intersections are separated by a distance shorter than 500 m, though the *p*-value of 0.14 was marginally higher than the 0.10 commonly used for statistical significance purposes. In addition, presence of separate left-turn lanes, number of intersection approach lanes, vehicle class, number of vehicles involved, posted speed limit, and seatbelt usage all appeared to have a significant effect on the risk of fatality. However, a fairer analysis of the impact of diverse factors on crash severity would be performed using a multivariate model, as fatality risk would be investigated while multiple variables would be controlled for simultaneously. After applying the model building procedures described in [73], the model shown in Table 5 was found. Correlation analysis was carried out and it was observed no statistically significant correlation among variables included in the model building process.

The model contained in Table 5 indicates that the odds of fatal injury occurrence are: (i) 1.7 times more likely to occur at locations where intersections are separated by a distance of more than 500 m as compared to locations where intersections are separated by a distance shorter than 500 m, (ii) higher at intersections with no or only a single left-turn lane than at intersections with multiple left-turn lanes, (iii) higher at intersections with longer left-turn lanes, (iv) higher when unbelted occupants are involved in a crash, (v) higher in multiple-event crashes (i.e., hitting roadside hazards, running over a human or bicycle, or rollover), and (vi) higher when there was no access point upstream intersection.

Table 5. Multivariate Signalized Intersection Model.

Variable	Non-Baseline Category	Baseline Category	Total # Observations	# Non-Baseline Observations	Odds	*p*-Value	ANOVA *p*-Value	GOF (*p*-Value)
Distance Between Signalized Intersections	>500 m	≤500 m		620	1.7	0.19	0.19	
Presence of Separate Left-Turn Lanes	No Lanes Single Lanes	Multiple Lanes	940	117 463	2.6 2.3	0.17 0.05	0.14	0.66
Length of Left-Turn Lane	-	-		-	1.002	0.12	0.12	
Seatbelt Usage	No	Yes		365	6.2	0.00	0.00	
Number of Crash Events	Multiple	One		241	2.1	0.06	0.06	
Presence of Access Points	No	Yes		799	3.03	0.01	0.01	

The variable "Distance Between Signalized Intersections" was broken down into ">500 m" and "≤500 m", which are thresholds different from those used for the variable "Distance Between Roundabout and Nearest Intersection" (see Table 3). The reason for this is that there would be a small sample for roundabouts with distance of 500 m or less (i.e., 78 out of 581). Likewise, only 15% of the crashes occurred on locations where intersections were separated by a distance larger than 1 km since the majority of the signalized intersection locations were urban areas.

The variable "Presence of Access Points" identifies whether there was an access point upstream the intersection or not. If the distance between intersections was 1 km or more, then the presence of access points was checked for only 1 km distance. However, if the distance between the intersections was shorter than 1 km, then the presence of access points was checked for the entire distance between the intersections. Moreover, access point presence was identified for the intersection arm on which the driver at fault was driving [74].

Lastly, the Hosmer-Lemeshow, goodness-of-fit (GOF) test indicated that this model presented an acceptable fit based on a *p*-value of 0.66, significantly higher than the critical value of 0.05.

3.2. Risk Factors Associated with Roundabout Crashes

Table 6 shows the results from the univariate analysis conducted using the roundabout crash data only. Posted speed limit, approach curvature, distance between pedestrian crosswalk to the roundabout yielding line, roundabout island diameter, width of the entry approach, number of approach lanes, presence access points upstream roundabout approach, distance between roundabout and nearest intersection, rollover, lighting condition, vehicle class, number of vehicles involved, number of crash events, seatbelt usage, and driver's gender were all considered further into the multivariate analysis (i.e., based on a *p*-value of 0.25 or lower). After applying the model building procedures described in [73], the multivariate model shown in Table 7 was selected. Correlation analysis was carried out and it was observed no statistically significant correlation among variables included in the model building process.

As can be seen, the model shown in Table 7 indicates that the odds of fatal injury occurrence are higher: (i) as the width of the entry approach increases, (ii) as the roundabout island diameter increases, (iii) as rollovers occur, (iv) where there is no road lighting or where it was in poor condition, (v) in multiple-event crashes, (vi) when unbelted occupants were involved in a crash, and (vii) as driver at fault was female.

Finally, the goodness of fit of this model was also found to be adequate based on a *p*-value equal to 0.46.

Table 6. Univariate Analysis: Roundabouts.

Variable	Non-Baseline Category	Baseline Category	Total # Observations	# Non-Baseline Observations	Odds	*p*-Value	ANOVA *p*-Value
Posted Speed Limit (kph)	≥80	≤60	794	209	1.39	0.25	0.265
Approach Curvature	-	-	674	-	1.0015	0.25	0.25
Distance Between Pedestrian Crosswalk and the Yielding Line	-	-	235	-	1.0009	0.12	0.12
Roundabout Island Diameter	-	-	794	-	1.0015	0.07	0.07
Width of Entry Approach	-	-	682	-	1.13	0.05	0.05
Number of Approach Lanes	≥3	≤2	681	366	1.6	0.12	0.12
Presence of Access Points	No	Yes	683	239	1.46	0.18	0.18
Distance Between Roundabout and Nearest Intersection	>1 km	≤1 km	581	300	1.8	0.08	0.08
Rollover	Yes	No	794	230	2.2	0.01	0.01
Lighting Condition	Poor or no Light	Sufficient Light	794	43	2.3	0.07	0.07
Vehicle Class	Light Vehicle	Heavy Vehicle	758	663	2.5	0.13	0.13
Number of Vehicles Involved	Single Vehicle	Multiple Vehicle	794	566	1.9	0.08	0.08
Number of Crash Events	Multiple Events	Single Event	794	422	3.82	0.00	0.00
Seatbelt Usage	No	Yes	770	335	2.01	0.02	0.02
Gender	Female	Male	787	66	1.66	0.23	0.23

Table 7. Multivariate Roundabout Model.

Variable	Non-Baseline Category	Baseline Category	Total # Observations	# Non-Baseline Observations	Odds	*p*-Value	ANOVA *p*-Value	GOF (*p*-Value)
Width of Entry Approach	-	-		-	1.2	0.06	0.06	
Roundabout Island Diameter	-	-		-	1.0021	0.07	0.07	
Rollover	Yes	No		188	1.9	0.05	0.05	
Lighting Condition	Poor or No Light	Sufficient Light	654	34	3.2	0.02	0.02	0.46
Number of Crash Events	Multiple Events	Single Event		360	3.9	0.00	0.00	
Seatbelt Usage	No	Yes		304	2.0	0.03	0.03	
Gender	Female	Male		54	2.5	0.04	0.04	

3.3. In-Service Safety Performance Evaluation: Signalized Intersections versus Roundabouts

The model presented in this section intends to address the second objective of this study (see Section 1.2): to compare the in-service safety performance of signalized intersections and roundabouts. In this analysis, crash severity was set as the dependent variable, while intersection type was defined as an independent variable. After applying the model building procedures described in [73], the multivariate model shown in Table 8 was selected. Correlation analysis was carried out and it was observed no statistically significant correlation among variables included in the model building process.

As can be seen, the model shown in Table 8 indicates that the odds of fatal injury occurrence are 1.8 times higher for signalized intersection crashes than those for roundabout crashes while controlling for the presence of access points, lighting condition, object struck, and seatbelt usage.

Table 8. Multivariate Roundabout Model.

Variable	Non-Baseline Category	Baseline Category	Total # Observations	# Non-Baseline Observations	Odds	*p*-Value	ANOVA *p*-Value	GOF (*p*-Value)
Intersection Type	Signal	Roundabout		607	1.8	0.12	0.12	
Presence of Access Points	No	Yes		370	1.9	0.02	0.02	
Lighting Condition	Poor or No Light	Sufficient Light	1462	40	2.2	0.12	0.12	0.51
Object Struck	None Roadside Hazard	Vehicle		45	0.5	0.50	0.09	
				427	1.9	0.07		
Seatbelt Usage	No	Yes		524	2.3	0.00	0.00	

4. Discussions and Conclusions

The present study analyzed 2008 intersection-injury crashes that occurred in the Emirate of Abu Dhabi between 2012 and 2017. Results from this study indicate that the risk of fatalities increased as:

(i)   signalized intersections are separated by longer distances and have no access point upstream, which may be explained by the fact that these characteristics may be associated with roads with higher posted speed limits and, therefore, may result in crashes involving faster traveling vehicles. Previous research has shown that adding merging lanes for inbound vehicles, near intersections, can improve road safety [75]. These merging lanes have the potential to reduce interactions among inbound and merging vehicles;

(ii)   signalized intersections had no or only one left-turn lane, which may be explained by the fact that intersections with no or only one left-turn lane may involve permitted rather than protected left-turning movements. That is, intersections with no or only one-left turn lane were located on 2-lane roads carrying lower traffic volumes and, therefore, left-turning movements were not protected. This confirms findings from previous studies [76,77];

(iii)   signalized intersections contained longer left-turn lanes, which may be explained by the fact that longer left-turn lanes were more likely to be present at intersections with larger to left-turning traffic, increasing the chance of crashes involving more severe impact conditions (e.g., near head-on impacts);

(iv)   signalized intersection or roundabout crashes involved more than one event such as multiple-event crashes involving vehicles running off the road, hitting curbs, and other roadside hazards located in the median;

(v)   signalized intersection or roundabout crashes involved unbelted vehicle occupants. In fact, crashes involving unbelted occupants were over six times more likely to result in fatalities as compared to crashes not involving unbelted occupants. This provides evidence for the case to strive for absolute compliance to seatbelt usage in order to improve safety;

(vi)   roundabouts have wider entry approaches and larger center islands. This may be explained by the fact that roundabouts with these characteristics allow for faster traveling speeds;

(vii)   roundabouts have no or poor lighting. It was often described in the crash description fields that the occurrence of roundabout crashes were often influenced by the driver's inability to see the roundabout. This finding highlights the importance of proper signage and/or lighting at roundabout locations;

(viii)   roundabout crashes involved rollovers. Many of these rollover events occurred after vehicles hit curbs. Previous studies showed that a significant portion of the roadside design adopted in the Emirate of Abu Dhabi is non-compliant to state-of-the-art guidelines largely due to excessively high curbs [78], which may likely have contributed to vehicle instability, eventually resulting in rollovers; and

(ix)   crashes occurred at signalized intersections rather than at roundabouts. Indeed, the odds of fatal injury occurrence was found to be 1.8 times higher at signalized

intersections as compared to roundabouts while controlling for the presence of access points, lighting condition, object struck, and seatbelt usage, though this finding is based on a *p*-value marginally higher than the widely used 0.10 threshold.

In sum, the findings from the present study provide road designers with input on factors that contribute to fatal signalized intersection and roundabout crashes, as well as decision-makers with much needed locally-produced scientific evidence, that converting existing roundabouts into signalized intersections actually deteriorates road safety, increasing the fatality risk of the motoring public in the UAE. It is important to note, however, that there may be other factors influencing intersection safety that might not have been captured by the data used in the statistical modeling adopted in this study. As such, road safety audits/inspections may be undertaken as an attempt to collect data on control variables that were missing in the database (and therefore not included in this study), but that still might affect safety [79]. Nonetheless, the findings of this research should also benefit neighboring GCC countries considering their similarities in road design, traffic characteristics, and driving culture.

5. Recommendations

The significant amount of evidence available in the literature, as well as the findings from this study, back the idea that there are safety benefits associated with the conversion of signalized intersections to roundabouts. It is important to stress that the present study indicated that there are safety benefits to be reaped from roundabout adoption even though operating speeds prevailing on Abu Dhabi's roundabouts may be too high [68]. These excessively high operating speeds may be attributed to both reckless driving behavior [67] as well as large roundabout diameters. In Abu Dhabi, roundabouts usually have multiple lanes, resulting in large diameters. In fact, the median diameter of the roundabouts included in this present study was found to be 61 m. Such wide diameters augment the tendency for higher operating speeds. A such, these large Abu Dhabi roundabouts might not have produced the safety benefits that they could have had were they smaller.

Recent research has proposed some design modifications to the traditional roundabouts as a means to improve safety. That is, turbo roundabouts have been proposed as a mean to decrease conflict points associated with merging/exiting or lane-changing movements [80]. Indeed, research has shown that turbo roundabouts produce safety benefits in relation to traditional roundabouts [81–84]. Features such as lane dividers and spiral road markings may have contributed to improved safety associated with turbo roundabouts [85,86].

Thus, based on past research findings and research findings from the present study, it is recommended that roundabouts be preferred due to their safety benefits. As mentioned previously, more recent research has suggested that these safety benefits may even be increased if turbo roundabouts are used [82,83]. However, given that roundabouts may be replaced by signalized intersections due to operational reasons (i.e., to decrease intersection delay/congestion during certain times), the authors recommend road design and decision-makers to ask the following questions before giving the go-ahead to projects which may primarily be concerned with increased car-mobility levels at intersections, especially during peak hours:

(i) In the case of new projects: are the economic benefits associated with decreased delay being traded-off against an increase in the risk of injury or death?

(ii) In the case of retrofitting projects (i.e., in the form of a roundabout replacement by a signalized intersection), can the economic benefits associated with decreased peak delay offset an increase in the risk of injury or death plus the design/construction/maintenance cost associated with traffic signal operation?, and

(iii) Is net daily delay associated with the adoption of a signalized intersection decreased or increased? Here, net daily delay is defined as the delay reduced during the peak hour plus the delay increased during off-peak hours due to red-light-waiting times.

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