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Evaluating safety effectiveness of roundabouts in Abu Dhabi

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ABSTRACT

With more than 460 roundabouts located in Abu Dhabi, the capital city of the United Arab Emirates, it is imperative to evaluate the safety benefits provided by those roundabouts. In this study, two approaches were used to evaluate those safety benefits. The first approach is by measuring the 85th percentile operating speeds at a sample of 18 roundabouts in Abu Dhabi to determine whether the measured operating speeds conform to what is recommended by design guides. The second approach is by using a questionnaire to measure how drivers in Abu Dhabi perceive safety when driving at roundabouts and to measure their level of knowledge regarding the rules pertaining to driving at roundabouts. The study found that operating speeds at Abu Dhabi roundabouts typically exceed those recommended by design guides. The study also found that only 4.1% of the drivers interviewed demonstrated a comprehensive understanding of the rules pertaining to driving at roundabouts. Ordinal regression modeling was used to identify driver groups in need for more awareness of the rules to negotiate roundabouts in Abu Dhabi. The study found that the driver group in most need for more awareness is typically young and middle-age male drivers (below the age of 46 years) with less driving experience in countries where roundabouts are common. The questionnaire also revealed that despite the operational benefits provided by roundabouts (in terms of reduced delay), drivers do not prefer to drive at Abu Dhabi roundabouts, which might be explained by drivers' perception of Abu Dhabi roundabouts being not safe.

1. Introduction

There are more than 460 roundabouts in Abu Dhabi, the capital city of the United Arab Emirates. Most of those roundabouts are multi-lane roundabouts with three entry/circulatory/exit lanes. A main advantage of roundabouts, as compared to conventional intersections, is their geometric features that help reducing the frequency and severity of traffic collisions by reducing the number of conflict points and forcing drivers to reduce their speeds [1–6]. Persaud et al. [7] observed significant reduction in collisions after converting signalized and stop-controlled intersections into roundabouts where the reduction in all collisions was 40% and the reduction in injury collisions was 80%. Similar findings were observed by Schoon and Van Minnen [8] where they observed reduction in all collisions by 47% and in injury collisions by 71%. Troutbeck [9] observed 74% reduction in injury collisions following the conversion of 73 roundabouts in Victoria, Australia. Several other studies observed similar findings [10–13]. Based on those studies, it may be concluded that the following two conditions must be met for a roundabout to reduce the frequency and severity of traffic collisions:

a) The design of the roundabout must conform to the design guides [2,14] as well as the best practices so that the geometry of the roundabout would force drivers to reduce their speeds without causing unnecessary delays; and
b) Drivers must be familiar with the rules of driving at roundabouts [15–17]. This is usually achieved through proper education, licensing procedures, and law enforcement techniques.

As for the first condition related to the speed at roundabouts, it was previously found that higher operating speeds at roundabouts are usually associated with an increase in the frequency and severity of collisions [2,10,18,19]. As for the second condition related to drivers' familiarity with the rules of driving at roundabouts, it was found that drivers' confusion and unfamiliarity with roundabouts would usually lead to an increase in the frequency of collisions [15–17].

The purpose of this study is to evaluate the effectiveness of Abu Dhabi roundabouts in improving safety through two approaches. The first approach is by observing the 85th percentile operating speeds at 18 roundabouts in Abu Dhabi and comparing those operating speeds with what is recommended by design guides [2,14]. The second approach is by using a questionnaire to measure how drivers perceive safety and proper driving rules when driving at Abu Dhabi roundabouts. This study also identifies driver groups in need for better education

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regarding proper rules when driving at roundabouts. The following section provides details on data collection, followed by another section that provides details on data analysis and discussion of the results. Conclusions and recommendations are also provided.

2. Data collection

As was previously discussed, the process of data collection involves the following two tasks:

a) The first task is to measure the 85th percentile operating speeds at 18 roundabouts in Abu Dhabi and compare those speeds with the values recommended by design guides; and
b) The second task is to use a questionnaire with a representative sample of drivers in Abu Dhabi to measure how those drivers perceive safety and proper driving rules when driving at roundabouts.

The following two subsections provide details on data collection related to each of the two tasks.

2.1. Measuring 85th percentile operating speeds

The 85th percentile operating speeds at 18 roundabouts in Abu Dhabi were measured using Bushnell Velocity speed guns, which are capable of measuring vehicle speeds from 16 km/h to 322 km/h at a range up to 457 m with an error of approximately ± 2 km/h [20]. The 85th percentile operating speed is the speed below which 85% of drivers travel [21,22]. All the roundabouts selected for the study have three entry/circulatory/exit lanes. It must be noted that most roundabouts in Abu Dhabi and its surrounding suburban areas also have three entry/circulatory/exit lanes. Since weekends in Abu Dhabi are on Fridays and Saturdays, speeds were measured on typical weekdays of Mondays, Tuesdays, or Wednesdays. Speeds were measured during 1 h within the morning peak period (that typically occurs between 7:30 AM and 9:30 AM), 1 h within the afternoon peak period (that typically occurs between 2:30 PM and 4:30 PM), and 1 h within the evening peak period (that typically occurs between 6:30 PM and 8:30 PM). The three peak periods shown are identified according to the data provided by Abu Dhabi Department of Municipal Affairs and Transport. Those three peak periods are different from peak periods in many other countries due to the differences in weather conditions, typical business hours, and travel habits in Abu Dhabi. Fig. 1 shows satellite images (obtained from Google Earth) of the 18 roundabouts selected for the study. All the roundabouts in the sample were designed according to Abu Dhabi geometric design guide, which is mainly derived from the US design guide [14]. Hourly traffic volumes and the geometric characteristics of all roundabouts were obtained from Abu Dhabi Department of Municipal Affairs and Transport. Those hourly volumes, geometric characteristics, and locations (latitudes and longitudes) are all shown in Table 1. The geometric characteristics shown in Table 1 include the entry radius, R_1, the radius of the central island, R_2, the exit radius, R_3, and the diameter of the inscribed circle, D_I. Those geometric characteristics are shown in Fig. 2. For every possible vehicle path through a roundabout (turning right, turning left, going through, or making a U-turn), speeds were measured at the following three locations, as shown in Fig. 2:

a) Entering speeds were measured for vehicles entering the roundabout along the entry path arc;
b) Circulating speeds were measured for vehicles traveling at the roundabout around the central island; and
c) Exiting speeds were measured for vehicles exiting the roundabout along the exit path arc.

To avoid the cosine effect associated with the use of radar guns [23], speeds were measured as close as possible to a collision course with the target vehicles to minimize the angle of incidence. This is illustrated in Fig. 2, which shows that the speed guns were placed, in relation to any entry or exit arm, at point “A” to measure entering speeds, point “B” to measure circulating speeds, and at point “C” to measure exiting speeds. To avoid sampling bias, the speed of only the first vehicle was measured in cases when vehicles were traveling in platoons. As shown in Table 2, there was a total of 26,991 speed observations obtained and used to calculate the 85th percentile speeds. Those observations include 9335 observations taken in the morning, 8763 observations taken in the afternoon, and 8893 observations taken in the evening. It must be noted that the 85th percentile operating speeds were measured at the three locations (entering, circulating, and exiting) of each arm of the roundabout for different vehicles. It must also be clarified that the scope of this research was to measure the 85th percentile operating speed at each of the three locations and not to establish a speed profile for each vehicle.

With a population of approximately 1.15 million and an area of approximately 970 km^2, the greater Abu Dhabi area (including its surrounding suburban areas) represents an interesting case study with more than 460 roundabouts. The selection of the 18 roundabouts included in the study was quasi random and motivated by the desire to have a representative sample of roundabouts in Abu Dhabi. As shown in Fig. 3, the 18 roundabouts included in the study are scattered throughout Abu Dhabi and its surrounding areas. Furthermore, the 18 roundabouts included in the study have varying geometric and traffic characteristics, as shown in Table 1, and varying land uses, as shown in Fig. 1. These variations provide an opportunity to observe drivers' behavior when driving at different roundabouts with diverse geometric, traffic, and land-use characteristics.

2.2. Measuring drivers' perception of safety and proper driving rules

A questionnaire was designed for this study to measure how drivers perceive safety and proper driving rules when driving at Abu Dhabi roundabouts. Tables 3 and 4 show the questions included in each of the two parts of the questionnaire along with all the possible responses to each question. The first seven questions (from Q1 to Q7) are used to identify different characteristics related to the respondent (age, gender, and driving experience). The last seven questions in Table 3 (from Q8 to Q14) are used to evaluate the respondent's level of knowledge pertaining to the rules when driving at roundabouts. The five questions shown in Table 4 (Q15 to Q19) are used to measure the respondent's perception of safety when driving at roundabouts in Abu Dhabi. Prior to distributing the questionnaire, ethical clearance was obtained from the Institutional Review Board at Abu Dhabi University. Hard copies of the questionnaire were printed and distributed to respondents who were visiting the local traffic department office to renew their drivers' licenses or vehicles' registration. The respondents' arrival at the traffic department office was completely at random. The study team approached the respondents at the site during regular business days and the respondents' participation was random and voluntarily. Statistical power analysis indicates that with a sample size of 543 respondents and a population of approximately 420,000 drivers in Abu Dhabi, the confidence interval is approximately 4.2% at 95% confidence level. Given the large Arabic-speaking population as well as the large English-speaking population in Abu Dhabi, both Arabic and English versions of the questionnaire were available so that respondents may fill out the version they felt more comfortable with.

It must be noted that there is only one correct answer, shown in italic, for each of the last seven questions in Table 3 (from Q8 to Q14). The Road User Code of the Emirate of Abu Dhabi [24] was used to identify those correct answers. Based on that, every respondent received a score based on his/her knowledge of proper driving rules at roundabouts. That score was based on the number of correct answers given by the respondent to questions Q8 through Q14. That score ranged from zero-out-of-seven (if all the answers given by the respondent to the seven questions were incorrect) to seven-out-of-seven (if all the answers given by the respondent to the seven questions were correct).

Fig. 1. Satellite images of the study sites (map data ©2018 Google).

3. Data analysis and results

3.1. Operating speeds

The measured 85th percentile entering, circulating, and exiting speeds of all the sites are shown in Table 5. The mean (and standard deviation) values are also shown in Fig. 4. As shown in Table 5, the entering speeds in 7 out of the 18 roundabouts exceed the target entering speed of 40–48 km/h as was recommended by design guides [2,14]. This seems to be attributed to the use of large radii of the entry curves. Furthermore, circulating speeds in 7 out of the 18 roundabouts exceed the maximum circulating speed of 50 km/h as recommended by design guides [2,14]. This seems to be attributed to the use of large radii of the central islands as shown in Fig. 1. By comparison, a previous research

Table 1
Site characteristics.

Site	Hourly traffic volume			R_{entry} (m)	$R_{central}$ (m)	R_{exit} (m)	D_I (m)	Latitude	Longitude
	Morning	Afternoon	Evening						
1	1765	1145	1315	31.15	31.35	33.55	86.75	24°21′33.18″N	54°30′06.30″E
2	1315	980	1055	32.15	36.20	35.65	92.40	24°21′17.14″N	54°30′07.46″E
3	980	745	815	34.25	21.25	41.25	72.60	24°24′52.35″N	54°27′51.79″E
4	965	775	765	31.40	18.15	41.65	62.30	24°24′41.87″N	54°30′24.17″E
5	1240	1135	1315	38.15	22.10	41.10	81.25	24°26′26.66″N	54°21′40.15″E
6	1045	715	685	27.15	22.10	53.15	81.20	24°25′09.18″N	54°32′48.81″E
7	1655	1425	1155	39.30	20.70	61.25	59.70	24°24′17.95″N	54°30′16.42″E
8	1440	1125	1335	41.25	25.30	55.65	86.35	24°22′05.53″N	54°30′04.39″E
9	450	325	310	28.90	15.45	31.20	51.60	24°24′26.51″N	54°29′44.23″E
10	1015	615	585	32.50	32.85	61.45	91.25	24°27′07.04″N	54°21′01.23″E
11	625	610	530	37.55	21.80	61.25	80.45	24°24′20.58″N	54°36′19.10″E
12	455	235	215	28.70	16.15	41.20	51.60	24°25′25.20″N	54°33′45.03″E
13	865	915	960	26.35	15.50	31.45	53.40	24°24′37.81″N	54°29′48.30″E
14	1325	1415	1625	33.60	25.35	53.05	89.40	24°21′35.36″N	54°30′59.77″E
15	775	810	830	24.15	24.20	33.25	83.10	24°26′50.42″N	54°22′10.07″E
16	1135	1025	1330	36.25	32.30	66.35	86.45	24°27′18.04″N	54°22′03.07″E
17	635	615	550	37.85	21.50	44.30	82.30	24°21′48.97″N	54°32′43.02″E
18	950	915	935	26.65	30.90	33.85	83.30	24°21′41.30″N	54°33′18.42″E
Minimum	450	235	215	24.15	15.45	31.20	51.60	–	–
Mean	1035.28	862.50	906.11	32.63	24.06	45.59	76.45	–	–
Maximum	1765	1425	1625	41.25	36.20	66.35	92.40	–	–
Std. dev.	366.27	316.69	379.32	4.88	6.14	11.56	13.73	–	–

study was conducted to measure the 85th percentile speeds at 98 roundabout approaches in the United States [25] found that the mean 85th percentile entering speed was 34.9 km/h (with a standard deviation of 3.9 km/h). In another study to measure the 85th percentile speeds at 7 roundabouts in Italy [26], the mean 85th percentile circulating speed was found to be 34.9 km/h (with a standard deviation of 6.3 km/h). Kim and Choi [27] measured the 85th percentile operating speeds at 14 roundabouts in South Korea where they found that the mean entry, circulating, and exit speeds, along with their respective standard deviations, were (26.3 ± 5.2) km/h, (23.2 ± 4.0) km/h, and (27.0 ± 6.3) km/h, respectively. Rubio-Martín et al. [28] presented a case study for a roundabout in Spain where the mean values and standard deviations of entry, circulating, and exit speeds were estimated to be (35.1 ± 4.3) km/h, (33.3 ± 4.6) km/h, and (38.4 ± 7.6) km/h,

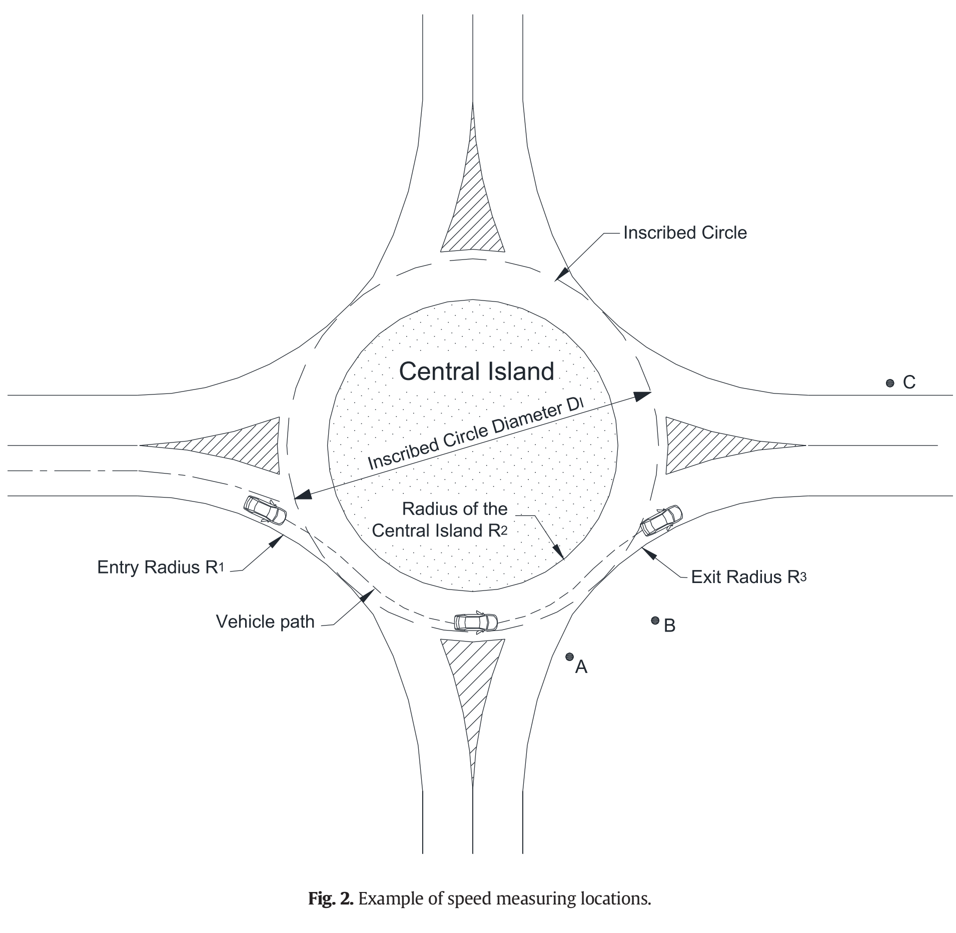

Fig. 2. Example of speed measuring locations.

Table 2
Number of observations used.

Site	Morning			Afternoon			Evening			Total			
	Day 1	Day 2	Day 3	Day 1	Day 2	Day 3	Day 1	Day 2	Day 3	Morning	Afternoon	Evening	All
1	187	163	142	158	134	125	182	179	191	492	417	552	1461
2	148	153	179	156	188	139	124	129	173	480	483	426	1389
3	112	107	109	119	127	142	101	133	142	328	388	376	1092
4	130	137	133	128	124	116	128	124	120	400	368	372	1140
5	193	166	181	188	176	149	163	148	177	540	513	488	1541
6	201	126	144	183	174	162	134	112	144	471	519	390	1380
7	214	243	201	193	217	205	173	174	162	658	615	509	1782
8	211	169	177	198	174	188	214	244	196	557	560	654	1771
9	187	164	188	132	115	143	155	177	143	539	390	475	1404
10	223	210	202	201	177	163	193	232	202	635	541	627	1803
11	214	179	163	188	201	178	193	189	163	556	567	545	1668
12	165	185	193	132	116	144	158	144	166	543	392	468	1403
13	108	114	123	87	124	102	99	101	134	345	313	334	992
14	204	232	201	188	221	165	193	208	236	637	574	637	1848
15	119	178	133	208	187	163	232	214	185	430	558	631	1619
16	163	196	154	167	154	211	188	163	178	513	532	529	1574
17	207	174	169	133	141	125	111	102	118	550	399	331	1280
18	208	217	236	196	212	226	211	175	163	661	634	549	1844
All sites	3194	3113	3028	2955	2962	2846	2952	2948	2993	9335	8763	8893	26,991

respectively. Pilko et al. [29] measured operating speeds at four roundabouts in Zagreb, the capital city of Croatia, where they found those operating speeds to be typically below 33.9 km/h. Based on these studies, the measured operating speeds at Abu Dhabi roundabouts are typically higher than those in other parts of the world. Those excessive speeds seem to be mainly attributed to the use of large radii used in Abu Dhabi roundabouts. As an example, Table 1 shows that the mean value of the inscribed circle diameter in Abu Dhabi is (76.45 ± 13.73) m. By comparison, the mean values of the inscribed circle diameter in South Korea and Serbia were (37.88 ± 14.08) m and (36.20 ± 1.47) m, respectively [27,30]. In addition to the geometric features that are overly designed, as shown in Fig. 1 and Table 1, driver behavior might also be a contributing factor for those excessive speeds, which will be discussed in the following subsection.

3.2. How drivers perceive safety and proper driving rules

A total of 543 respondents participated in the survey with the distributions of their answers to different questions are shown in Tables 3 and 4 for the two parts of the questionnaire, respectively. Fig. 5 shows the distribution of respondents who received different scores ranging from zero-out-of-seven to seven-out-of-seven. Only 4.1% of the respondents demonstrated complete understanding of the rules pertaining to driving at roundabouts in Abu Dhabi (with a score of seven-out-of-seven). The average score of all respondents was 3.57 out of 7 (with a standard deviation of 1.57). This finding suggests that more efforts are needed to increase drivers' awareness of the rules pertaining to negotiating roundabouts in Abu Dhabi.

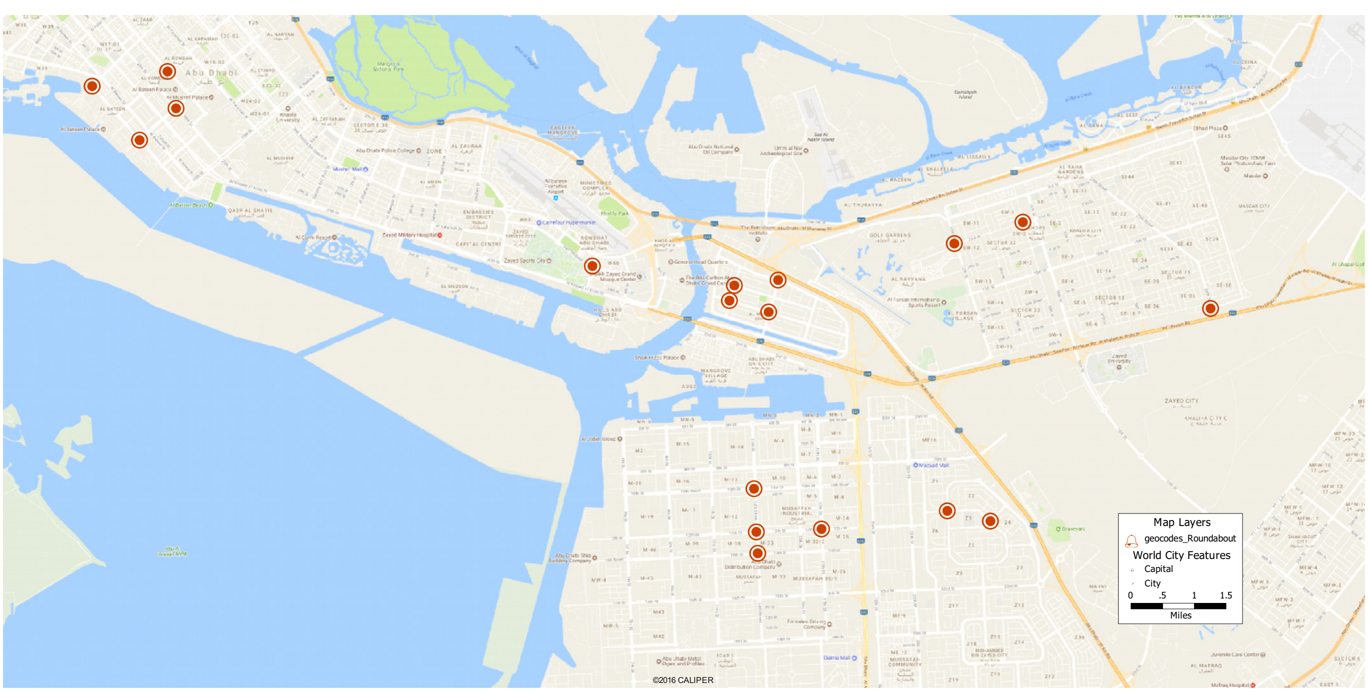

Fig. 3. Map showing the locations of the study sites throughout the city of Abu Dhabi and its surrounding suburban areas (map data ©2018 Google).

Table 3
Questions (and response rates) included in the first-part of the questionnaire.

Question	Possible responses					
Q1. What is your age group (in years)?	18–25 (6.1%)	26–35 (19.8%)	36–45 (21.9%)	46–55 (22.5%)	56–65 (26.2%)	65+ (3.5%)
Q2. What is your gender?	Male (83.4%)			Female (16.6%)		
Q3. How many years of driving experience do you have in Abu Dhabi?	0–1 (3.1%)	1–2 (3.1%)	2–3 (16.6%)	3–4 (22.1%)	4–5 (11.8%)	5+ (43.3%)
Q4. How many years of driving experience do you have in any Gulf Council Country (GCC)?	0–1 (77.3%)	1–2 (5.9%)	2–3 (8.3%)	3–4 (7.2%)	4–5 (0.6%)	5+ (0.7%)
Q5. How many years of driving experience do you have in any of the following countries (Australia; United Kingdom; New Zealand; or any European Union country)?	0–1 (79.6%)	1–2 (3.3%)	2–3 (0.7%)	3–4 (0.7%)	4–5 (8.5%)	5+ (7.2%)
Q6. How many years of driving experience do you have in any countries that are not listed in questions 4 and 5?	0–1 (19.8%)	1–2 (23.5%)	2–3 (28.9)	3–4 (12.4%)	4–5 (6.3%)	5+ (9.1%)
Q7. How many years of total driving experience do you have in all countries?	0–1 (0.4%)	1–2 (2.0%)	2–3 (6.8%)	3–4 (4.6%)	4–5 (3.1%)	5+ (83.1%)
Q8. If there are no other vehicles near you, do you ever reduce your speed when entering a roundabout?	*Yes*[a] (50.8%)			No (49.2%)		
Q9. Do you usually use the roundabout's lane corresponding to your entry lane (for example you use the outer lane of the roundabout if you are coming from the outer lane of the road)?	*Yes*[a] (48.4%)			No (51.6%)		
Q10. When driving at a roundabout, do you try to keep your vehicle in the same lane until you exit the roundabout?	*Yes (I only change the lane when exiting the roundabout)*[a] (52.9%)			No (I usually change the lane within the roundabout) (47.1%)		
Q11. When you wait to enter a roundabout, do you usually make sure that your vehicle is outside the lane marking of the outermost circulatory lane of the roundabout?	*Yes*[a] (53.6%)			No (46.4%)		
Q12. When entering a roundabout, do you ever cut-off in front of other drivers who are already at the roundabout and expect them to reduce their speeds accordingly?	Most of the time (12.5%)	Only when the roundabout is very busy (37.6%)		*I never do that*[a] (49.9%)		
Q13. Do you select a certain lane of the roundabout based on your intended path (for example you take the innermost lane if you intend to turn left)?	*Yes*[a] (51.6%)			No (48.4%)		
Q14. Do you always activate your right-turning signal when exiting a roundabout?	*Yes*[a] (50.3%)			No (49.7%)		

[a] Answers in italic are the correct answers according to the Road User Code of the Emirate of Abu Dhabi (Abu Dhabi Safety & Traffic Solutions Committee 2013).

Ordinal regression modeling was used to identify driver groups in need for more education regarding driving rules at roundabouts. This is based on the score received on the knowledge of proper driving rules at roundabouts (as identified by questions Q8 to Q14) as well as the respondents' characteristics (as identified by questions Q1 to Q7). For this purpose, a three-scale threshold system was created to describe each respondent's awareness of the rules pertaining to driving at roundabouts. The three scales include "*low awareness*" score (with 137 respondents having scores between 0 and 2), "*medium awareness*" score (with 250 respondents having scores between 3 and 4), and "*high awareness*" score (with 156 respondents having scores between 5 and 7). The developed ordinal regression model assumes the relationship:

$$z_i = \beta X_i + \varepsilon_i \tag{1}$$

In the above relationship, z_i is the dependent variable denoting the underlying function to estimate the level of awareness related to respondent i; β is a vector of parameters to be estimated; X_i is a vector of independent explanatory variables that define the characteristics of respondent i; and ε_i is the random error term. The random error term is assumed to follow normal distribution with zero mean and unit variance.

The dependent variable (the estimated level of awareness) may have one of the following estimates:

$$Y_{ij} = \left\{ \begin{array}{c} \text{"}\mathit{low\ awareness}\text{"} \text{ if } z_i < k_1 \\ \text{"}\mathit{medium\ awareness}\text{"} \text{ if } k_1 \le z_i < k_2 \\ \text{"}\mathit{high\ awareness}\text{"} \text{ if } z_i \ge k_2 \end{array} \right\} \tag{2}$$

Table 4
Questions (and response rates) included in the second-part of the questionnaire.

Question	Possible responses		
Q15. In general, how much safe do you feel when driving at roundabouts in Abu Dhabi?	I feel safer at roundabouts than at signalized intersections (20.5%)	I feel safer at signalized intersections than at roundabouts (52.9%)	I feel that both roundabouts and signalized intersections have the same level of safety (26.6%)
Q16. In general, do you feel that you experience increased delay at roundabouts in Abu Dhabi?	I experience more delay at roundabouts than at signalized intersections (27.4%)	I experience more delay at signalized intersections than at roundabouts (45.8%)	I experience same delay at both roundabouts and signalized intersections (26.8%)
Q17. Do you feel safer at roundabouts that have more or less number of lanes?	I feel safer when the roundabout has more lanes (31.2%)	I feel safer when the roundabout has less lanes (34.1%)	My feeling of safety is not affected by the number of lanes (34.7%)
Q18. Is your feeling of safe driving affected by the radius of the central island of the roundabout?	I feel safer with larger radius of the central island (40.6%)	I feel safer with smaller radius of the central island (24.1%)	My feeling of safe driving is not affected by the radius of the central island (35.3%)
Q19. In general, how do you prefer driving at roundabouts when compared to driving at signalized intersections?	I prefer driving at roundabouts (20.1%)	I prefer driving at signalized intersections (45.6%)	I have no specific preference (34.3%)

Table 5
Measured 85th percentile speeds (in km/h).

Site	Entering speed	Circulating speed	Exiting speed
1	36.9	47.6	49.3
2	42.6	49.2	50.7
3	50.0	48.9	53.6
4	47.8	46.9	49.8
5	44.8	53.1	56.4
6	44.4	48.4	53.2
7	48.9	54.6	59.3
8	47.9	48.9	54.2
9	57.2	52.7	59.3
10	53.4	61.2	63.4
11	60.6	67.2	68.9
12	60.7	68.4	69.2
13	37.4	41.4	44.1
14	34.6	39.4	47.8
15	37.3	42.3	48.1
16	42.4	44.3	48.5
17	60.4	57.1	59.8
18	38.3	44.8	46.8
Minimum	34.6	39.4	44.1
Mean	47.0	50.9	54.6
Maximum	60.7	68.4	69.2
Std. dev.	8.4	8.0	7.2

where k_1 and k_2 are thresholds for the levels of awareness related to respondent j, which are estimated by the model. The probability that a certain respondent, i, has different levels of awareness, j, may be calculated by the following:

$$P(Y_{ij} = \text{"}low\ awareness\text{"}) = P(z_i < k_1) = P((\beta X_i + \varepsilon_i) < k_1) = P(\varepsilon_i < (k_1 - \beta X_i)) \quad (3)$$

$$P\left(Y_j = \text{"}medium\ awareness\text{"}\right) = P(k_1 \leq z_i < k_2) = P(\varepsilon_i < (k_2 - \beta X_i)) - P(\varepsilon_i < (k_1 - \beta X_i)) \quad (4)$$

$$P\left(Y_j = \text{"}high\ awareness\text{"}\right) = P(z_i \geq k_2) = 1 - P(\varepsilon_i < (k_2 - \beta X_i)) \quad (5)$$

The parameters of the ordered model are estimated using a maximum likelihood estimation method by performing systematic evaluation of the function at different points to find the point at which the function could be maximized. The Wald test is used to test the statistical significance of each of the estimated coefficients ($\beta_1, \beta_2, \beta_3 \ldots \beta_k$). Given that $\hat{\beta}_i$ is the i^{th} estimated model coefficient and $SE(\hat{\beta}_i)$ is the standard error of that coefficient, the Wald statistic is computed as:

$$Wald = \left[\hat{\beta}_i / SE\left(\hat{\beta}_i\right)\right]^2 \quad (6)$$

The estimated ordered probit model is shown in Table 6, and the estimated marginal effects are shown in Table 7. The coefficients (and standard errors) shown in Table 6 are estimated at 0.05 significance level. The coefficient *Kappa* is the difference between thresholds k_1 and k_2 shown in Eq. (2) through Eq. (5). The bottom two rows of Table 6 represent the Bayesian Information Criterion (BIC) and Akaike Information Criterion (AIC) associated with different variables. It must be noted that the age groups shown in Table 6 are selected based on the fact that more than 80% of the population in Abu Dhabi are non-citizen expatriates between 25 years and 55 years of age. As shown in Table 3, only 6.1% of the respondents were in the age group of 18–25 years; and therefore, this age group was combined with the age group of 26–35 years to form the age group of drivers below the age of 36 years shown in Table 6. Similarly, only 3.5% of the respondents were in the age group above 65 years; and therefore, this age group was combined with the age group of 56–65 years to form the age group of drivers above the age of 55 years shown in Table 6. Consequently, the four age groups reported in Table 6 that return meaningful statistical results are (a) drivers below the age of 36 years; (b) drivers between 36 years and 45 years; (c) drivers between 46 years and 55 years; and (d) drivers above the age of 55 years.

In addition to the fixed-parameter ordered probit model, shown in Table 6, another random-parameter ordered probit model was also estimated to account for any possible unobserved heterogeneity in the data. For the random-parameter ordered probit model, two variables were selected to have random distribution that proxied the extent of drivers' experience in jurisdictions where roundabouts represent a regular feature. The first random variable selected was the number of years driving in Abu Dhabi and other Gulf Council countries (GCC). The second random variable selected was the number of years driving in other countries where roundabouts are common (Australia, United Kingdom, New Zealand, and EU countries). The estimated coefficients of the fixed parameter and random-parameter models were found to be almost identical to each other. This is due to the statistically insignificant coefficients associated with the standard deviations of the random parameters, indicating that random heterogeneity is not present in the analyzed data. This conclusion is also supported by the Log-likelihood value associated with the random-parameters model, which is also

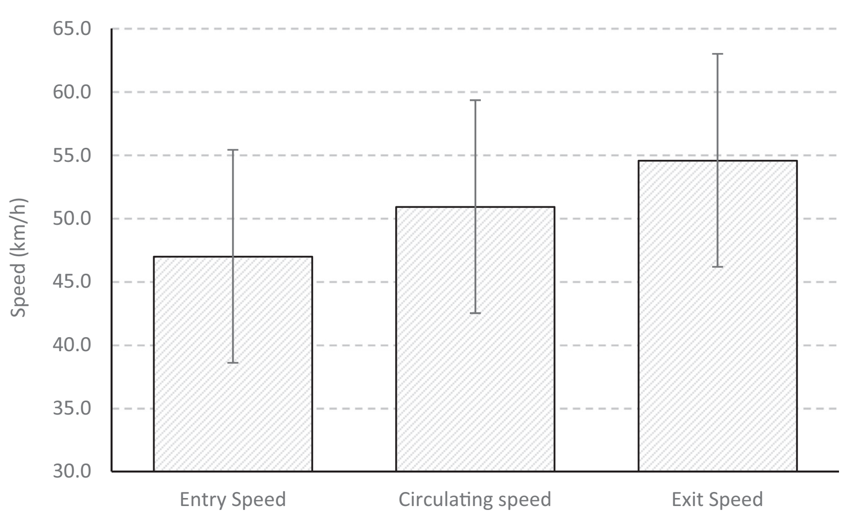

Fig. 4. Measured mean (and standard deviation) of entry, circulating, and exit speeds.

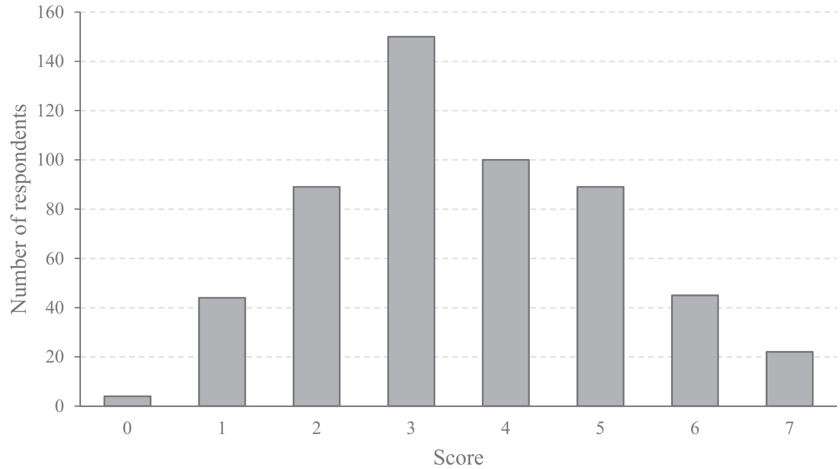

Fig. 5. Score distribution of survey respondents.

almost identical to that associated with the fixed-parameter model, meaning that assuming random heterogeneity in the data did not improve the model. Due to the insignificance of the random-parameter model, it was not reported in Table 6.

As shown in Table 6, the most significant variables associated with higher knowledge scores are when the driver is above the age of 46 years and when the driver has experience in driving in other countries where roundabouts are common (Australia, United Kingdom, New Zealand, and EU countries). Experience in driving in Abu Dhabi or other Gulf Council countries is also associated with higher knowledge score to a less extent than the aforementioned factors. Female drivers were also found to have higher knowledge scores than male drivers. Therefore, it could be concluded that the driver group in most need for more awareness are typically young and middle-age male drivers (below the age of 46 years) with less driving experience in countries where roundabouts are common (Australia, United Kingdom, New Zealand, and EU countries).

The estimated marginal effects for each parameter, over the three different awareness levels, are shown in Table 7. Those marginal effects are used to estimate the three levels of awareness of driving regulations related to roundabouts in Abu Dhabi. As shown in Table 7, approximately 25.4% of drivers are estimated to have a low level of awareness of the rules to negotiate roundabouts in Abu Dhabi. Approximately 45.6% of drivers are estimated to have a medium level of awareness of the rules to negotiate roundabouts in Abu Dhabi. Finally, approximately 28.9% of drivers are estimated to have a high level of awareness of the rules to negotiate roundabouts in Abu Dhabi.

As for drivers' perception of safety at roundabouts, Table 4 shows that the majority of the respondents (72.6%) reported that they experience reduced delay at roundabouts than at signalized intersections, which is expected given the known benefits of roundabouts in reducing delay. However, only 20.5% of the respondents reported that they feel safer at roundabouts than at signalized intersections, and only 20.1%

Table 6
Estimated coefficients (and standard errors) of the ordinal model.

Parameter	Coefficient
Kappa	1.832 (0.097)
Constant	−0.652 (0.140)
Driver's age	
Below 36 years	Reference category
36–45 years	0.179 (0.164)[a]
46–55 years	0.558 (0.179)
Above 55 years	0.604 (0.155)
Driver's gender	
Male	Reference category
Female	0.424 (0.149)
Years of driving experience	
In Abu Dhabi and GCC countries	0.204 (0.033)
In other countries where roundabouts are common	0.977 (0.162)
Number of observations	543
Log-likelihood	−384.445
BIC	819.267
AIC	784.890

[a] The estimated coefficient is not significant at the 0.05 significance level.

Table 7
Estimated marginal effects associated with all covariates in the ordinal models.

Covariate	Margin	Standard error	z	P > |z|	95% confidence intervals	
Awareness level:						
Low	0.254	0.017	15.16	0.000	0.221	0.287
Medium	0.456	0.019	23.81	0.000	0.419	0.494
High	0.289	0.013	22.82	0.000	0.264	0.314
Female driver:						
Low	−0.106	0.037	−2.890	0.004	−0.178	−0.034
Medium	0.037	0.014	2.590	0.010	0.009	0.065
High	0.069	0.024	2.840	0.005	0.021	0.117
Driver's age: 36–45 years:						
Low	−0.045	0.041	−1.100	0.272	−0.124	0.035
Medium	0.015	0.014	1.110	0.267	−0.012	0.043
High	0.029	0.027	1.080	0.280	−0.024	0.082
Driver's age: 46–55 years:						
Low	−0.140	0.043	−3.210	0.001	−0.225	−0.054
Medium	0.048	0.016	2.960	0.003	0.016	0.080
High	0.091	0.030	3.040	0.002	0.032	0.150
Driver's age: over 56 years:						
Low	−0.151	0.037	−4.040	0.000	−0.224	−0.078
Medium	0.052	0.015	3.490	0.000	0.023	0.082
High	0.099	0.026	3.780	0.000	0.048	0.150
Driving experience in Abu Dhabi and GCC:						
Low	−0.051	0.008	−6.610	0.000	−0.066	−0.036
Medium	0.018	0.004	4.450	0.000	0.010	0.025
High	0.033	0.006	5.970	0.000	0.022	0.044
Driving experience in other roundabout countries:						
Low	−0.245	0.041	−5.910	0.000	−0.326	−0.163
Medium	0.085	0.023	3.640	0.000	0.039	0.130
High	0.160	0.025	6.500	0.000	0.112	0.208

of the respondents reported that they prefer to drive at roundabouts than at signalized intersections. For comparison, in a previous study by Savolainen et al. [31] it was found that only 29.3% of drivers in Michigan feel safer at roundabouts while the majority (52.7%) reported that they feel less safe at roundabouts. An interesting finding of this study is that the majority of the respondents (65.9%) reported that they feel safer at roundabouts with more lanes. This is despite the known fact that collision frequency increases when roundabouts have more lanes [2,32]. This finding emphasizes how the public may inaccurately perceive risk due to the use of cognitive heuristics in sorting and simplifying information, which may lead to biases in comprehension [33,34]. Another interesting finding is that 40.6% of the respondents reported that they feel safer when driving at roundabouts with larger radii of the central island. This may be due to the psychological effect that a larger safety margin is provided to those drivers. However, it should be noted that when drivers feel more comfortable driving at roundabouts with large radii of the central island, those drivers may increase their speeds, which may lead to an increase in the frequency of collisions at those roundabouts [2].

4. Conclusions

In this study, safety benefits at roundabouts in Abu Dhabi were measured using two approaches. The first approach was by measuring the 85th percentile entering, circulating, and exiting speeds at 18 roundabouts in Abu Dhabi using speed guns. It was found that operating speeds at Abu Dhabi roundabouts typically exceed the maximum speeds recommended by design guides. Those excessive speeds seem to be mainly attributed to the overly-designed geometric features of roundabouts in Abu Dhabi such as the radii of the entry curves and the central islands. The second approach to measure safety benefits related to roundabouts in Abu Dhabi was by using a questionnaire to measure how drivers in Abu Dhabi perceive safety and rules pertaining to driving at roundabouts. The questionnaire included 7 questions that are designed to measure the level of knowledge pertaining to driving at roundabouts in Abu Dhabi. It was found that only 4.1% of the respondents who participated in the questionnaire demonstrated comprehensive understanding of the rules pertaining to driving at roundabouts in Abu Dhabi. Ordinal regression modeling was used to identify driver groups in need for more awareness of the rules pertaining to driving at roundabouts in Abu Dhabi. It was found that driver groups in most need for more awareness are typically young and middle-age male drivers (below the age of 46 years) with less driving experience in countries where roundabouts are common (Australia, United Kingdom, New Zealand, and EU countries). The questionnaire also revealed that only 20.5% of the respondents reported that they feel safer at roundabouts than at signalized intersections, and only 20.1% reported that they prefer to drive at roundabouts than at signalized intersections. This finding indicates that despite the operational benefits provided by roundabouts (in terms of reduced delay), users do not prefer to drive at Abu Dhabi roundabouts due to the decrease in their perception of safety. An interesting finding of this study is that the majority of the respondents (65.9%) reported that they feel safer at roundabouts with more lanes. This opinion is contrary to the fact that collision frequency increases with the increase in the number of lanes at roundabouts. This finding emphasizes how the public may inaccurately perceive risk due to the use of cognitive heuristics in sorting and simplifying information, which may lead to biases in comprehension. It must be noted that the results reported in this research are limited to roundabouts in Abu Dhabi given their unique characteristics as was reported in this research.

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