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Assessing the Effect of Geometric Design and Land Use on Roundabouts Using Video Camera

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Abstract

This study is concerned with assessing the effect of geometric design and land use on roundabouts, which are one of the most widely used traffic calming techniques. It aims to study the speed profiles before, at, and after thirty selected roundabouts in Jordan to develop models for predicting the circulating speed for through movement as a function of the land use of the roundabout, the roundabout geometric characteristics, and the approaching highway free-flow speed. A laser radar gun was used to capture speed data, and geometric characteristics were extracted from video pictures. Various parameters were employed to simulate the circulating speed, including the roundabout diameters, free flow speed, entry deviation angle, approaching highway exit width, circulating roadway width, and entry width. Speed profiles were developed for six roundabout types with different land uses and geometric characteristics. It was found that the roundabout effect on speed reduction extends to 150 m downstream the exit and upstream the entry. It was also discovered that the rate of reduction varies according to the upstream street free flow speed (FFS), with dramatic decreases observed at the last 50 m upstream of the entry. Variability in the speed values around the midpoint of the circulatory roadway was observed, with speed at the exit being higher than that at the entry.

Keywords: Roundabouts; Land Use; Free Flow Speed; Circulating Speed; Laser Radar Gun.

1. Introduction

Roundabouts are commonly used in Jordan to control traffic at urban and suburban at-grade intersections since they are less expensive and more successful at controlling traffic than other at-grade intersection traffic control options. Stop signs and traffic signals are regarded as less secure than roundabouts for directing traffic at grade intersections. This is because, in comparison to other at-grade intersection traffic control technologies, roundabouts offer a unique geometric shape that reduces merging and diverging conflict spots while providing no crossing conflict points. Also, they provide a continuous movement for road users, which makes them preferable to users.

The present paper studies the effect of the approach geometric conditions and land use upstream and downstream of the roundabout on the speed profile and speed reduction rates of six selected roundabouts (with 6 land-use types: residential, agricultural, recreational, institutional, and public buildings (PB), commercial, and industrial) with their upstream and downstream approaches that serve the through traffic movements to investigate the speed-space relationship as drivers approach and leave these roundabouts. The selected vehicle class for this study is the passenger

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car. The proposed models could be used as predictors for roundabout circulating speed and examined to see if they satisfy safety requirements.

According to guidelines provided by the US Federal Highway Administration (FHWA), modern roundabouts are a type of circular intersection including channelized approaches, yield control at the entry, and a geometric curve that slows heading traffic. The Transportation Research Board (TRB) compared two-way stop-control (TWSC), all-way stop-control (AWSC), signaled intersections, and roundabouts and concluded that, for the same traffic volume, roundabouts offer less delay and greater capacity. When demand exceeds capacity at a minor approach of TWSC, a roundabout offers an appropriate solution to the left turn movements. A roundabout that works around its capacity generates lesser delay than a signalized intersection, resulting in reduced fuel usage and pollutant emissions [1]. Other advantages of roundabouts were presented by Woodmansey and Spalding (2012) [2]. They reported that roundabouts would minimize travel times, decrease collision severity and rates, limit the requirement for acquisition, and boost capacity. In addition to being less expensive than signalized crossings, the roundabout approach would more effectively handle access management and other community goals [3-6].

Roundabouts have lower accident severity rates, as most accident types can be categorized under Property Damage Only (PDO) [4]. After creating accident models based on the kind of land use, Lee et al. (2016) [6] indicated that roundabout accident variables differ according to circumstances. They could determine that adding more speed breakers to commercial areas and enlarging the inscribed circle in residential and business zones will help lower the frequency of accidents. Lee et al. (2016) [6] concluded that the speed transition distance (the point at which the vehicle's speed begins to decelerate) is a function of the internal circle diameter, as indicated in Equation 1, and that linear modeling is recommended for establishing the speed-pace relationship.

$$d_{12,m}=1.153\ D_{INT}+2.9853 \tag{1}$$

where D_{INT} is diameter of the internal circle (m), $d_{12,m}$ is speed transition distance.

Two studies were conducted in Italy to determine the parameters impacting the roundabout's circulating speed. Three statistically significant factors were found by Sacchi et al. (2011) [5] to be associated with the operating speed of 35 urban roundabouts: the width of the entry lane, the width of the circulation path, and the diameter of the internal circle. Additionally, Antov et al. (2009) [7] investigated the factors influencing driver speed choice at roundabouts by analyzing speed data collected via video recording at 11 roundabouts (3268 vehicles). The inscribed circle diameter of the roundabout was the primary element influencing driver speed choice; it had a similar effect on drivers of all vehicle classes but with a lower mean speed for heavy vehicles than for passenger cars. Additionally, roundabout speeds were around half those of the link speeds between intersections. Due to the roundabout configuration, vehicles must first turn to the right, then turn to the left as they pass around the circle, and then return to the right again after clearing the circle. The combination of these turns, deflection at the entry point, and counterclockwise circulation around the center island helps calm the approaching traffic at the intersection. Meanwhile, due to their high operating speeds, roundabouts with very large islands are not considered traffic-calming techniques [8, 9].

Hels et al. (2007) [10] used Poisson and logistic regression analyses to demonstrate a relationship between the annual rate of cyclist accidents and roundabout geometry, traffic volume, and intersection age. In order to assess the thorough circulating route deflection connected to the length of the road deflected during circulating, the researchers developed a new variable called drive curve. Significant predictors of roundabout traffic accidents were found to be vehicle speed and roundabout age [11]. The accident probability was shown to be higher for older roundabouts. According to Poisson models, roundabouts with a bigger drive curve had a higher crash probability, as higher driving speeds could be achieved within these roundabouts. Alshannaq & Imam (2020) [12] also discovered that insufficient signage at roundabout entry, disregarding traffic laws, and a lack of clearly visible lane markings in the circulating area were the primary causes of roundabout accidents.

Akcelik (2018) [13] stated that roundabout delay depends on its geometric characteristics, negotiation radius, distance, and corresponding speeds, as it compels drivers to slow down at roundabouts. In their observation of 14 roundabouts in Jordan, Al-Omari et al. (2004) [14] emphasized geometric factors linked with roundabout delay, using video data gathered at approaches for a total of 20 hours to build a roundabout delay model. The diameter of the roundabout, the width of the circulating roadway, the width of the entering roadway, the volume of the entering highway, and the volume of the circulating roadway were used to forecast the roundabout entrance delay.

Other researchers dealt with various aspects of roundabout capacity and safety levels. For example, Akeclik and Rod (2021) [15] compared their findings of capacity and saturation estimation (v/c ratio), level of service, delay, and queue length estimation using the HCM 2010 model to those from the roundabout SIDRA Standard Capacity model. Due to changes in driver behavior, roundabouts in the United States of America were found to have a lower capacity than those in the United Kingdom and Australia. Wong and Yang (2012) [16] evaluated Beijing's roundabout capacity using weaving section gap acceptance and discovered that conflict and interference occur rapidly at weaving sections, resulting in a decrease in speed. Al-Masaeid (1999) [17] observed roundabout entry capacity and performance and observed that evaluating roundabout operation based on drivers' gap-acceptance behavior when entering a roundabout would be more meaningful. The chance that a randomly chosen motorist would accept a specific gap in the moving traffic was predicted using the logit model. Al-Masaeid & Faddah (1997) [18] used regression analysis on data collected from ten roundabouts in Jordan to construct an empirical model for evaluating roundabout capacity. The center island diameter, entry and exit distances, circulating traffic volume, and circulating breadth were all taken into account while modeling the capacity of roundabout entrances.

Zirkel et al. (2013) [19] investigated the relationship between roundabout safety and traffic operational parameters. They discovered that greater differences in entrance and approach speeds result in increased collision rates. At sites with longer sight distances, significant speed differences were detected. They advocated the development of performance-based design principles to set threshold values that increase roundabout traffic safety. According to Chen et al. 2013 [20], the average entry, circulation, and departure widths, as well as the average diameters of the central island and inscribed circle, all influence the average approach speed (AAS). The average of the entrance, upstream circulation, and departing speeds was referred to as the AAS. Italy was found to have marginally quicker speeds than the US, according to a categorical variable that was introduced to the module to represent data from either country [20]. The findings showed that roundabouts have a greater AAS when their average diameter and breadth are larger. In order to build roundabout collision prediction models, Daniels et al. (2011) [21] included in their investigation a variety of road users, including pedestrians, motorcyclists, moped riders, passenger automobiles, and large four-wheel vehicles. Al-Madani (2003) [22] used a video recording data collection method to compare vehicular delay between traffic signals and police-controlled roundabouts. They discovered that when similar geometric characteristics of intersections are considered, a critical value of traffic delay exists where the two control types exhibit identical delay values. The roundabout delay is smaller before this critical value, whereas the signal delay is smaller after this critical value [23, 24]. This means that roundabouts are preferable to traffic signals when traffic volumes are low to medium, while traffic signals are preferable to roundabouts when traffic volumes are high.

The approach FFS had the strongest linear correlation with both the average and 85^{th} percentile circulating speed. Entry width, exit width, and diameter exhibit a moderate correlation. Circulating width was found to have a weak relationship with the average circulating speed, and the entry angle was found to have a weak negative linear relationship. The roundabout diameter had the greatest impact in predicting the average circulating speed, while entry width was the least important in predicting such speed [25]. The average circulating speed model outperformed the 85^{th} percentile speed model. The 85^{th} percentile circulating speed model variables were exit width and approach FFS. The predictors of land use, entry width, circulating width, entry angle, and diameter were omitted by the stepwise analysis, where the FFS of the approach had the highest impact in the 85th percentile circulating speed model [26].

It is necessary for traffic engineering to have a methodology for estimating the speed profiles before, at, and after roundabouts in different land uses for the purpose of operational, design, and planning analysis. A large number of studies have been conducted on different issues related to roundabouts; however, less attention has been given to speed performance [27].

Research identifies key contributing factors related to speed at roundabouts: insufficient entry and circulatory lanes, uneven traffic distribution, and high overall traffic volume. A detailed case study of the south leg highlights the severity of the situation, with the Level of Service (LOS) dropping to F during evening hours, resulting in long queues (over 61 vehicles) and delays exceeding 82 seconds per vehicle. This study proposes exploring design optimization of the roundabout [28]. In the study, the criticality of roundabouts, in terms of their geometric design as well as the provided road safety, lies upon the fact that roundabouts are currently used for the conventional vehicle fleet, which will be gradually replaced by new vehicle technologies. Such an action will directly impact the criteria for road network design and/or redesign, thereby continuously fostering new research initiatives [29].

In their study, Tumminelo et al. (2024) [30] explored the domain of intelligent transportation systems, specifically focusing on roundabouts as potential solutions in the context of smart mobility. Roundabouts have been found to offer a safer and more efficient driving environment compared to other intersections. The synthesis review supported the authors in presenting current knowledge and emerging needs in roundabout design and evaluation. A focused examination of the models and methods used to assess the safety and operational performance of roundabout systems was necessary. This is particularly relevant in light of new challenges posed by the automotive market and the influence of vehicle-to-vehicle communication on the conceptualization and design of this road infrastructure. Special or improper designs of roundabout configurations or basic geometry elements could arouse roundabout conflicts.

The most common vehicle-to-vehicle conflicts were entering-circulating conflicts, sideswipe conflicts, and exiting-circulating conflicts. The conflicts among vehicles and vulnerable road users (VRUs) easily evolved into serious collisions, but these conflicts did not get the deserved attention in previous studies. Drivers' familiarity with roundabouts also affected road users' safety. Traffic signs and pavement markings were commonly used to control roundabout conflicts, while traffic signals were more effective methods for the roundabouts with uneven distribution of approaching traffic or high traffic volume [31].

Brewer et al. (2023) [32] investigated the operational and safety benefits of modern roundabouts and selected innovative intersection designs for high-speed locations, as well as the best practices for designing these intersection alternatives. In the project, the research team compiled proven results from these designs in other states and collected and analyzed operational and safety data within Texas to develop updated design guidance. Suleiman et al. (2024) [33] developed a tool to improve the traffic safety level on roundabouts and identify the influence of traffic operations, geometric parameters, weather, and time of day on improving roundabout traffic safety. Analysis of Variance (ANOVA) was used to validate data related to roundabout safety. Traffic distribution, geometric design at roundabout, time of day, surface conditions and average speed were studied. Geometric design parameters such as inside and outside radius, number of lanes, conflict length, and number of legs for each roundabout were collected from relevant authorities. It was recommended to reduce the allowable vehicle speed and apply traffic monitoring and inelegant management methods to segregate vehicles in time and space.

Pham & Nguyen (2024) [34] used in their investigation one-way ANOVA followed by the Duncan test at a significant level of 5% to test the relationship between air quality parameters and microclimate factors using Pearson correlation. Principal component analysis (PCA) was utilized to identify critical variables and potential sources. Abdulkathum et al. (2023) [35] aimed to verify the scour depth around different shapes of uniform bridge piers for different flow conditions than those done by previous researchers using different prediction models. Multiple linear Regression Analysis and statistical analyses should take this into account to ensure the efficiency and adequateness of the results. To understand the behavior of all independent variables and their relationships with the dependent variable, the scour depth results of each model were studied and analyzed statistically with the benefit of some performance measures and the goodness of fit test. Bixhaku et al. (2023) [36] indicate that promoting cycling as a sustainable mode of transport necessitates understanding how individuals perceive the risks associated with bicycling based on age, gender, and riding experience. The study addresses a critical gap in the field of traffic by examining cyclists' perceptions of risk and safety on mixed-traffic roads. Descriptive Statistics, one-way ANOVA, and Pearson’s correction test were conducted to elicit perceptions based on age, gender, and experience.

Dabbour et al. (2018) [37] investigated 18 roundabouts in Abu Dhabi; the 85th percentile entering, circulating, and exit speeds were found to be 47, 50.9, and 54.5 km/h, respectively. By comparison, another study conducted at 98 roundabouts in the United States by Angelastro (2010) [38] found the mean 85th percentile entering speed to be 34.9 km/h. Bassani & Sacchi (2011) [39] found that the mean 85th percentile circulating speed in 7 roundabouts of Italy was 34.9 km/h. Kim & Choi (2013) [40] measured the 85th percentile operating speeds at 14 roundabouts in South Korea; they found that the mean entry, circulating, and exit speeds were 26.3, 23.2, and 27.0 km/h, respectively.

In the present research, an effort has been made to develop models for predicting the circulating speed for through movement as a function of the land use of the roundabout, the roundabout geometric characteristics, and the approaching highway free-flow speed. Speed data was collected using a laser radar gun during off-peak periods. In order to model the circulating speed of land uses at the roundabouts, approaching highways, free flow speed, entry width, circulating roadway width, exit width, roundabout diameter, and entry deviation angle were all used, and statistical regression analysis was applied to the data collected. Using a video camera and radar gun for this application, combining all these variables, and investigating different land uses add a new value to this research work.

2. Data Collection

In this section, necessary details on the process of the study methodology are provided and presented in a flowchart in Figure 1.

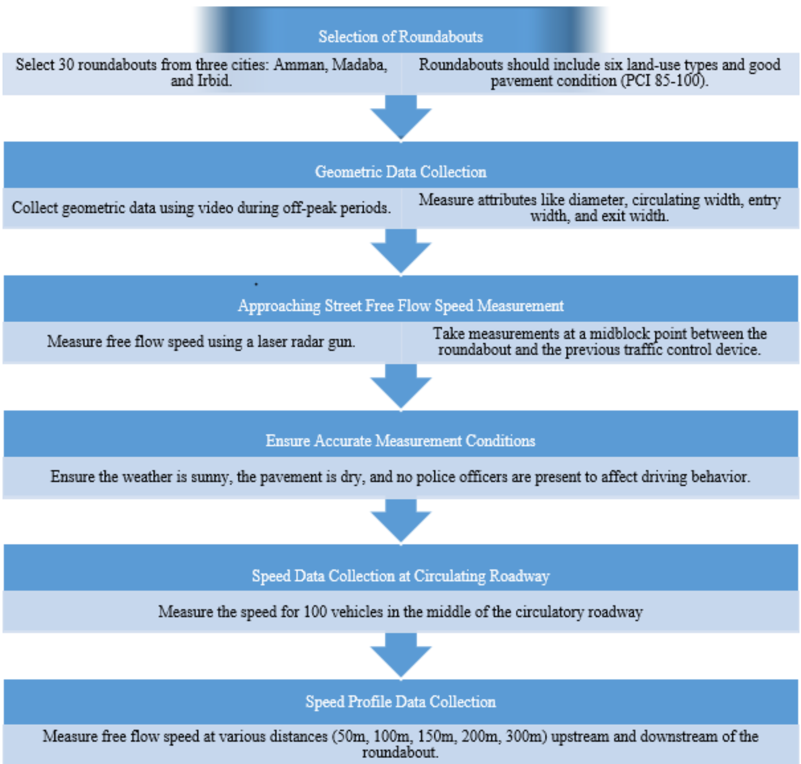

Figure 1. The workflow of the study

Thirty roundabouts of various sizes and characteristics are found in three major Jordanian cities, including Amman, Madaba, and Irbid. To reduce bias in the data that was gathered, the roundabouts were chosen from areas with nearly level and straight road alignments, respectable pavement conditions, and a fair distance from any significant traffic control devices or upstream or downstream traffic calming measures. As seen in Figure 2, geometric data was obtained using video footage collected during off-peak times (pictures). As seen in Figure 3, the physical characteristics upstream and downstream of the roundabout were diameter, circulating highway width, entry width, exit width, and entry angle.

Figure 2. Video Data (Images)

Drawing from the recorded video, the approaching street free flow speed was measured in the field at the midblock location between the roundabout entry and the previous significant traffic control device, or 300 meters, whichever was less. In the absence of police personnel, readings were obtained on sunny days with dry pavement. Approaching roadway free flow speed was monitored using a laser radar gun in the field at the midblock location between the last major traffic control device and the roundabout entry. Although laser radar gun readings are very accurate, the accuracy of radar units is affected by two errors: roundoff (rounding down to the nearest whole unit of speed) and angle units (the closer the angle to zero, the more accurate the speed measured; measurement is actual when the angle is zero).

Speed data collection was completed in two stages as follows:

- Stage one: for modeling speed at the circulating highway, 100 cars at each roundabout had their speeds monitored at one location in the middle of the route.
- Stage two: for speed profile development, the free flow speed was estimated at the following stations (with 100 measurements from each station) for each of the 6 selected types (land use) of roundabouts at 50, 100, 150, 200, and 300 m upstream of the roundabout entry, the middle of the circulatory roadway; the roundabout exit, and at 50, 100, 150, and 200 m downstream of the roundabout exit.

It is worth noting that only through-movement vehicles were considered for the speed profile observation. There was no unusual weather condition (rain, fog, or snow) that could have affected driver behavior. Off-peak hours were chosen for the speed of data collection in order to guarantee smooth traffic flow and the absence of conflicts or bottlenecks.

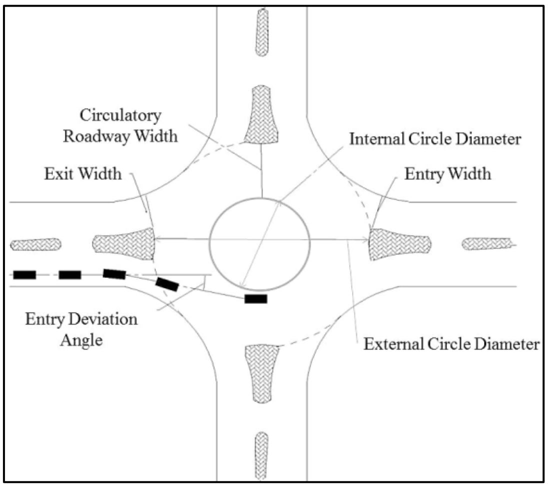

Figure 3. Roundabout Geometric Elements

The circulatory roadway superelevation, or the vertical height differential between the roundabout's inner and outer pavement boundaries, was also measured. The speed data was gathered on dry, bright days with no police activity using a laser radar gun. The previous principal traffic control device, which was 300 meters upstream of the entry, was used to compute the approaching street free flow speed (FFS). When there were no oncoming vehicles (a free-flow situation), the leading cars that arrived at the circular road entry were the ones whose roundabout circulation speed data was recorded during off-peak hours. In the center of the circulation path, 100 moving passenger automobiles provided the circulating speed data for each roundabout. Equation 2 was used to determine the sample size with regard to the real speed standard deviation (S), permitted errors (d) of 1, 3, and 5 km/h, and a 95% confidence interval [27]:

$$N = \left(\frac{ZS}{d}\right)^2 \tag{2}$$

where N is Minimum sample size, Z is Number of standard deviations corresponding to the required confidence (1.96 for 95% confidence level), S is Sample standard deviation (km/h), d is limit of acceptable error in the average speed estimate (km/h).

It was discovered that the sample size of 100 cars at each roundabout is greater than what is necessary for all three permitted error levels, with the exception of two that had an acceptable error of one km/h. The majority of traffic engineering studies typically assume an acceptable error of 3 km/h, and all roundabouts met this requirement for sample size. Table 1 defines the terminology used in this study, and Table 2 displays a summary of the features of the data that was gathered.

Table 1. List of Variables Used in the Study

Variables	Symbol	Units
Diameter	**D**	**Meter (m)**
Land use	L	1- Institutional and Public Buildings 2- Commercial 3- Industrial 4- Residential 5- Recreational 6- Agricultural
Entry Width	WE	M
Circulatory roadway width	WC	M
Exit width	WX	M
Entry deviation angle	AE	Radians
FFS of the upstream approach	VA	km/h

Table 2. Characteristics of the Collected Data

Variable	WE	WC	WX	D	AE	VA
Mean	6.93	7.42	6.73	33.4	0.28	56.8
Standard Deviation	1.09	0.97	1.32	16.6	0.13	14.8
Min	4.20	5.25	4.00	9.45	0.10	30.0
Max	9.95	9.00	9.00	70.0	0.52	78.0

3. Data Analysis

Each roundabout has two lanes on the north and south approaches and one on each of the east and west approaches. The circulating road has two lanes. The average speed measured was 35 km/h on the north approach, 30 km/h on the south approach, 25 km/h on the east approach, and 40 km/h on the west approach. The average speed along the circulation road was 20 km/h, and the super-elevation ranged from 2 to 3%.

3.1. Effect of Land Use on Average and 85th Percentile Circulating Speeds

One-way ANOVA was performed using SPSS software, where the effect of land use on both average and 85th percentile roundabout circulating speeds was estimated [23]. In addition, Tukey’s (HSD) test was conducted to evaluate the significant effect on the land use levels. As demonstrated in Table 3 by one-way ANOVA results, there was a statistically significant difference in both average and 85th percentile roundabout circulating speeds among the six land use categories, as p-values were less than 0.05.

Table 3. One-Way ANOVA Results of Land Use Effect on Average and 85th Percentile Roundabout Circulating Speeds

Dependent variable		Sum of Squares	df	Mean Square	F	Sig.
Average circulating speed	Between Groups	0310.32	05.000	62.064	20.248	0.000
	Within Groups	073.564	24.000	3.065		
	Total	**383.884**	**29.000**			
85^{th} percentile circulating speed	Between Groups	649.543	05.000	129.909	16.822	0.000
	Within Groups	185.340	24.000	7.722		
	Total	**834.883**	**29.000**			

Comparison of the means using the Tukey HSD test as summarized in Table 4 showed that there is a statistically significant difference in both average and 85^{th} percentile roundabout circulating speeds between the public building land use and the recreational, agricultural, residential, and industrial uses. Also, a significant difference was detected between commercial land use and recreational and agricultural ones, and between agricultural land use and residential and industrial ones ($p \leq .05$) [25].

Table 4. Tukey's (HSD) Results

Levels pairs	$V_{C,\ avg}$. Sig.	$V_{C,\ 85th}$ Sig.
Institutional vs Commercial	0.072	0.316
Institutional vs Recreational	0.000	0.000
Institutional vs Agricultural	0.000	0.000
Institutional vs Residential	0.000	0.001
Institutional vs Industrial	0.005	0.002
Commercial vs Recreational	0.013	0.015
Commercial vs Agricultural	0.000	0.000
Commercial vs Residential	0.290	0.131
Commercial vs Industrial	0.842	0.224
Recreational vs Agricultural	0.110	0.127
Recreational vs Residential	0.657	0.911
Recreational vs Industrial	0.163	0.781
Agricultural vs Residential	0.004	0.015
Agricultural vs Industrial	0.000	0.007
Residential vs Industrial	0.918	1.000

3.2. Effect of Land Use on Roundabout Geometric Parameters

The outcomes of the one-way ANOVA study on roundabout geometric characteristics, namely entry width, circulation width, entry angle, exit width, and diameter, for each form of land use, are displayed in Table 5. The *P*-value of entry and exit width was less than 0.05, which means that a statistically significant difference in entry and exit width due to land use was found.

Table 5. One-Way ANOVA Results

Dependent Variable		Sum of Squares	Df	Mean Square	F	Sig.
Entry Width	Between Groups	15.151	05	3.03	3.681	0.013
	Within Groups	19.756	24	0.823		
	Total	**34.907**	**29**			
Circulatory Width	Between Groups	08.944	05	1.789	2.295	0.077
	Within Groups	18.709	24	0.780		
	Total	**27.653**	**29**			
Entry Angle	Between Groups	00.071	05	0.014	0.862	0.521
	Within Groups	0.395	24	0.016		
	Total	**0.466**	**29**			
Exit Width	Between Groups	23.972	5	4.794	4.312	0.006
	Within Groups	26.685	24	1.112		
	Total	**50.657**	**29**			
Diameter	Between Groups	2619.22	5	523.844	2.31	0.076
	Within Groups	5441.767	24	226.74		
	Total	**8060.987**	**29**			

3.3. Pearson's Correlation Test

Pearson's correlation test was used to measure the direction and degree of the link between the average roundabout circulation speeds and the observed variables. According to Schober and Schwarte (2018) [26], the correlation coefficient ranges from (–1 to +1), with a value of (<0.1) denoting an insignificant connection, (0.1 - 0.4) denoting a weak correlation, (0.4 - 0.7) a moderate correlation, and (0.7 - 0.9) a strong correlation. Table 6 summarizes the findings.

Table 6. Correlation of Variables with Circulating Speeds

Variable	$V_{C,\ avg}$. Pearson's Correlation	$V_{C,\ 85th}$ Pearson's Correlation
Entry Width	0.57	0.564
Circulatory Width	0.334	0.327
Entry Angle	-0.273	-0.311
Exit Width	0.585	0.612
Diameter	0.525	0.402
FFS of the Approach	0.846	0.848

The approach FFS has the strongest linear correlation with both the average and 85th percentile circulating speeds. Entry width, exit width, and diameter exhibit a moderate correlation. Circulating width was found to have a weak relationship with the average circulating speed, and the entry angle was found to have a weak negative linear relationship.

3.4. Multiple Linear Regression Analysis

A regression analysis approach was utilized to predict the dependent variable (roundabout circulating speed) by examining a set of independent variables (geometric data along with land use data) using Equation 3.

$$V_{c,x}= f\,(L, W_E, W_C, A_E, W_X, D, V_A) \tag{3}$$

where Vx is Roundabout average circulating speed (km/h) where x denotes average or 85th speed, L is Land Use, WE is Entry Width (m), WC is Circulatory Width (m), AE is Entry Angle (radian), WE is Exit Width (m), D is Diameter (m), VA is FFS of the Approach.

3.4.1. Average Circulating Speed Model

The stepwise approach was utilized to carry out multiple linear regression. The process of building the regression model involved gradually adding and deleting predictors from the model until there was no more valid reason to do so. This allowed for the creation of a realistic and practical regression model. Only predictors with significant P-values at the designated 95% confidence level are included in the final model. The model is presented in Equation 4, as follows:

$$V_{c,avg} = 20.078 - 0.559\,L + 1.191\,WE - 1.522\,WC - 12.725\,AE + 1.045\,WE + 0.125\,D + 0.091\,VA \tag{4}$$

where $V_{c,avg}$ is Roundabout average circulating speed (km/h), L is Land Use, WE is Entry Width (m), WC is Circulatory Width (m), AE is Entry Angle (radian), WE is Exit Width (m), D is Diameter (m), VA is FFS of Approach (km/h).

The model achieved an R^2= 0.91 and an adjusted R^2= 0.881.

Multicollinearity is tested with two central criteria: tolerance, which measures the influence of one independent variable on all other independent variables (should be greater than 0.1), and Variance Inflation Factor (VIF), which is the ratio of the overall model variance to the variance of a model that includes only a single independent variable (should be less than 10).

The model was statistically significant, as shown in Table 7. In addition, all the geometric variables along with the land use variable were found to have a statistical impact on the estimation of the average circulating speed ($p \leq 0.05$). The coefficient of determination reflects a very good indicator of the prediction power of the estimated model (R^2= 0.91). Table 8 shows the coefficients of the developed model and the multicollinearity diagnostics.

Table 7. Average Circulating Speed Model Statistical Characteristics

	Sum of Squares	Df	Mean Square	F	Sig.
Regression	349.239	7	49.891	31.682	0.000
Residual	34.645	22	1.575		
Total	**383.884**	**29**			

Table 8. Regression Results for Average Circulating Speed Model

	Unstandardized Coefficients		Standardized Coefficients	T	Sig.	Collinearity Statistics	
	B	Std. Error	Beta			Tolerance	VIF
(Constant)	20.078	2.665		7.534	0.000		
Land Use	-0.559	0.208	-0.267	-2.695	0.013	0.418	2.394
Entry Width	1.191	0.453	0.359	2.630	0.015	0.220	4.542
Circulatory Width	-1.522	0.643	-0.409	-2.367	0.027	0.138	7.261
Entry Angle	-12.725	2.658	-0.443	-4.788	0.000	0.478	2.090
Exit Width	1.045	0.496	0.38	2.106	0.047	0.126	7.921
Diameter	0.125	0.021	0.575	5.944	0.000	0.438	2.281
FFS of Approach	0.091	0.028	0.374	3.272	0.003	0.315	3.179

Figure 4 depicts the *x*-axis of the model's predicted values while the *y*-axis shows the observed average circulating speeds; the diagonal line is the estimated regression line. As shown, the regression model fits the data reasonably; each data point is quite close to the regression line.

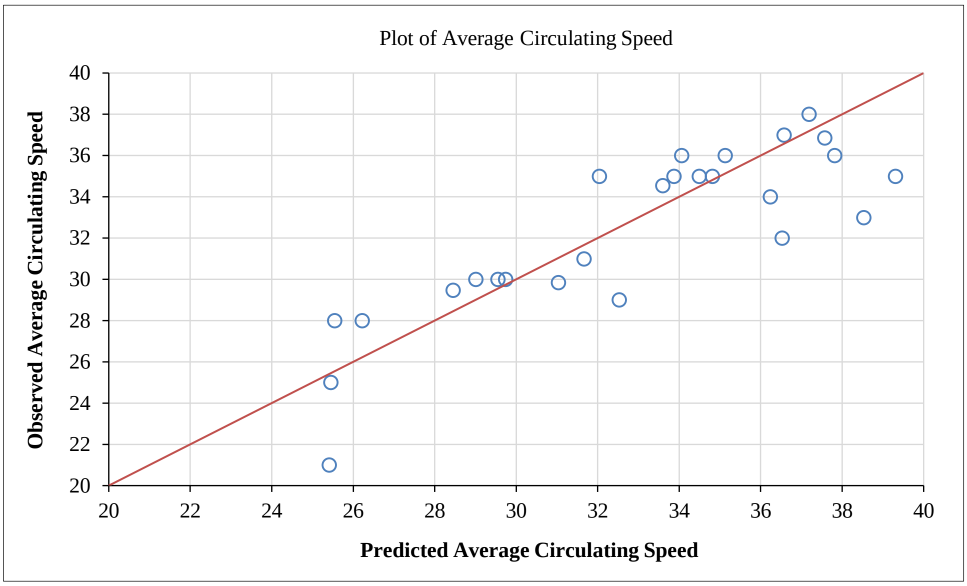

Figure 4. Predicted Versus Observed Average Circulating Speed

3.4.2. 85th Percentile Circulating Speed Model

The main predictors used in building the 85th percentile circulating speed model were exit width and the approach FFS. Land use, entry width, circulating width, entry angle, and diameter were omitted by the stepwise analysis. The 85th percentile circulating speed model was as in Equation 5:

$$V_{C,85th} = 12.536 + 0.938\, W_e + 0.262\, V_a \tag{5}$$

where $V_{c,85th}$ is Roundabout 85th circulating speed (km/h), W_E is Entry Width (m), V_A is FFS of Approach (km/h); the model had an R^2 is 0.758 and an adjusted R^2= 0.740.

As shown in Tables 9 and 10, the predicted model was significant at a 95% confidence interval; the exit width and the approach FFS were the main predictors with p-values less than 0.05, and the predictive power was reasonable with R2= 0.758. Collinearity was not detected (Tolerance >0.1 and the IVF <10). The FFS of the approach had a higher impact on the prediction model than the exit width.

Table 9. 85th Percentile Circulating Speed Model Statistical Characteristics

	Sum of Squares	Df	Mean Square	F	Sig.
Regression	632.59	2	316.295	42.216	0.000
Residual	202.293	27	7.492		
Total	**834.883**	**29**			

Table 10. Regression Results for 85th Percentile Circulating Speed Model

	Unstandardized Coefficients		Standardized Coefficients	T	Sig.	Collinearity Statistics	
	B	Std. Error	Beta			Tolerance	VIF
(Constant)	12.536	2.723		4.603	0.000		
Exist Width	0.938	0.452	0.231	2.076	0.048	0.725	1.38
FFS of Approach	0.262	0.040	0.727	6.530	0.000	0.725	1.38

The approach FFS had the strongest linear correlation with both the average and 85th percentile circulating speed. Entry width, exit width, and diameter exhibited a moderate correlation. Circulating width was found to have a weak relationship with the average circulating speed, and entry angle had a weak negative linear relationship. The roundabout diameter had the greatest impact in predicting the average circulating speed, while entry width was the least important in predicting such speed. The average circulating speed model outperformed the 85th percentile speed model. The 85th percentile circulating speed model variables were the exit width and approach FFS. In previous studies, the speeds are predicted based on the hourly traffic volumes, the proportions of heavy vehicles, and the geometric characteristics of the roundabouts. The models were validated with data not used in calibration, and they were found to be stable and robust.

4. Discussion

This paper aimed to study the effect of the approach geometric conditions and land use upstream and downstream of roundabouts on the speed profile and reduction rates along thirty selected roundabouts with 6 land-use types (residential, agricultural, recreational, institutional, and public buildings, commercial, and industrial) in three Jordanian cities. The goal was to investigate the speed-space relationship as drivers' approach and leave these roundabouts. As a traffic calming measure, it is observed that the roundabout has an effect on speed reduction that starts at around 150 m upstream of the entry and ends at 150 m downstream of the exit—but in the Merkblatt für die Anlage [26] The new information sheet takes into account the current state of knowledge on the various types of roundabouts in terms of application criteria and design elements. The consideration of pedestrian and bicycle traffic as well as public transport is also dealt with in depth. The lowest speed values were reached at the middle of the circulatory roadway, and the exit speed was found to be higher than the entry speed. However, in Berloco et al. (2022) [24], the main parameters responsible for a decrease in the deviation angle were a decrease in the inscribed circle diameter, a decrease in the angle between opposite legs, and an increase in the width of the circulatory lane. A comparison of the means using the Tukey HSD test showed that there was a statistically significant difference in both average and 85th percentile roundabout circulating speeds between the institutional and PB land use and the recreational, agricultural, residential, and industrial ones. The approach FFS had the strongest linear correlation with both the average and 85th percentile circulating speed. Entry width, exit width, and diameter exhibited a moderate correlation. Circulating width was found to have a weak relationship with the average circulating speed, and the entry angle had a weak negative linear relationship. The roundabout diameter had the greatest impact in predicting the average circulating speed, while entry width was the least important in predicting such speed. The average circulating speed model outperformed the 85th percentile speed model. The 85th percentile circulating speed model variables were the exit width and approach FFS. The predictors of land use, entry width, circulating width, entry angle, and diameter were omitted by the stepwise analysis. In Al-Moarawi & Essam (2018) [1], regression models were developed to predict the 85th percentile operating speeds at multilane roundabouts. Three models were developed to predict the entry, circulating, and exit speeds, where the FFS of the approach had the highest impact in the 85th percentile circulating speed model. Developing a prediction model for operational traffic speeds at roundabouts assists traffic agencies in selecting roundabout design features that can achieve specified operational speeds along roadways that are part of the traffic calming programs.

In Hossain et al. (2024) [28], analytical findings suggested that the comprehensive assessment of the capacity showed high traffic volume in both morning and peak period hours than the effective capacity of 2410 PCU/h. The capacity analysis of the Mintu Chattar roundabout reveals that most of the roundabout's legs are facing significant issues of oversaturation. It has been observed that during peak hours, traffic police intervention is required to manage traffic as the existing traffic control devices are unable to effectively regulate the flow. The level of service was found to be extremely low (LOS F), indicating a situation where the flow is forced or disrupted, and demand generally exceeds capacity. With the LOS at F, a backlog queue of 61.1 vehicles and 434.7 meters was observed, leading to an average delay of 82.4 seconds per vehicle. This delay is expected at LOS F. Enhancement strategies such as expansion of entry and circulatory lane width and increase of their number, along with required splitter islands and other traffic-controlling measures to control pedestrian movement, should be implemented on the Mintu Chattar roundabout. This includes investigating the impact of geometric redesigning, such as gradual expansion of approach lane width, on capacity at the roundabout leg, considering both existing and future traffic scenarios. However, in our study, statistical regression analysis was applied to the data collected from thirty roundabouts and showed that land use type of roundabout, approaching highway free flow speed, entry width, circulating roadway width, exit width, roundabout diameter, and entry deviation angle are all significant variables in determining the average circulating speed.

In Gkyrtis & Kokkalis (2024) [29], the criticality of roundabouts in terms of their geometric design as well as the provided road safety stems from the fact that roundabouts are currently used for the conventional vehicle fleet, which will be gradually replaced by new vehicle technologies. Such an action will directly impact the criteria for road network design and/or redesign, thereby continuously fostering new research initiatives. To achieve this objective, the role of micro-simulation studies was highlighted. Related research is ongoing, aiming at shedding light on the optimized geometric design of roundabouts with an efficient traffic flow, enabling both "safety" and "capacity" potentials to become maximized, thereby offering sustainable traffic management at roundabouts. But in our study, speed profiles were developed for all six roundabout types with different land uses and geometric characteristics. It was found that the roundabout effect on speed reduction extends to 150 m downstream of the exit and upstream of the entry. The speed-space relationship is not linear, and the rate of reduction varies according to the upstream street free flow speed (FFS), with dramatic decreases observed at the last 50 m upstream of the entry.

Tumminelo et al. (2024) [30] outlined areas for further research and developed perspectives on the role of roundabouts in the transition toward connected and autonomous vehicles and infrastructures. They concluded that the importance of roundabouts lies in their geometric design and the traffic-calming effect they provide, especially as conventional vehicle fleets are gradually replaced by new driving technologies. This shift will impact road network design criteria, leading to continued research in the field. Additionally, evaluation methods must be tailored to the new demands of cooperative driving to align with traffic management and urban planning objectives.

Li et al. (2024) [31] pointed out seven future directions of further research in terms of conflict measurement, data collection, infrastructure and access management, geometry, drivers and VRUs, signal control, and vehicle control. In our research, we focused on the effect of the approach geometric conditions and land use upstream and downstream of roundabouts on the speed profile and speed reduction rates to investigate the speed-space relationship as drivers approach and leave these roundabouts. The selected vehicle class for this study is the passenger car. The proposed models could be used as predictors for roundabout circulating speed and examine if they satisfy safety requirements.

In Brewer et al. (2023) [32], findings from simulation showed that a spacing of a minimum of 700 ft (230 m) between the main intersection and the downstream U-turn intersection resulted in higher operating speeds compared to a conventional signalized intersection. A spacing of 1,500 ft (492 m) or more generated 169 higher operating speeds for both the major and minor road drivers. As expected, operating speeds decreased as minor road, major road, or truck percentages increased. But in our research, for modelling speed at the circulating roadway, the speed was measured at one point in the middle of the circulatory roadway for 100 vehicles at each roundabout. For speed profile development, the FFS was measured at the following stations (with 100 measurements from each station) for each of the 6 selected roundabouts: the roundabout entry and at 50, 100, 150, 200, and 300 m upstream of the roundabout entry; the middle of the circulatory roadway; the roundabout exit; and at 50, 100, 150, and 200 m downstream of the roundabout exit. Only through movement were vehicles considered for the speed profile observation.

In this study, speed reduction rate is not linear upstream of the roundabout approach; instead, it increases dramatically in the last 50 m from the roundabout entry. The measured average entry, circulating, and exit speed values were 31.8, 27.8, and 32.8 km/h, respectively. Dabbour et al. (2018) investigated 18 roundabouts in Abu Dhabi, and the 85th percentile entering, circulating, and exit speeds were 47, 50.9, and 54.5 km/h, respectively. By comparison, another study conducted at 98 roundabouts in the United States by Angelastro (2010) found the mean 85th percentile entering speed to be 34.9 km/h. Bassani & Sacchi (2011) estimated the mean 85th percentile circulating speed at 7 roundabouts in Italy to be 34.9 km/h. Kim and Choi (2013) measured the 85th percentile operating speeds at 14 roundabouts in South Korea and found that the mean entry, circulating, and exit speeds were 26.3, 23.2, and 27.0 km/h, respectively. The findings of this paper are in general agreement with the results of previous studies. It is worth noting that the values for Abu Dhabi roundabouts are typically higher than those in other parts of the world. Those excessive speeds seem to be mainly attributed to the large radii used in Abu Dhabi roundabouts.

5. Conclusions and Future Directions

This study aimed to study the effect of the approach geometric conditions and land use upstream and downstream of roundabouts on the speed profile and reduction rates along thirty selected roundabouts with 6 land-use types (residential, agricultural, recreational, institutional, and public buildings, commercial, and industrial) in three Jordanian cities to investigate the speed-space relationship as drivers' approach and leave these roundabouts. As a traffic calming measure, it is observed that the roundabout has an effect on speed reduction that starts at around 150 m upstream of the entry and ends at 150 m downstream of the exit. The lowest speed values were reached at the middle of the circulatory roadway, and the exit speed was found to be higher than the entry speed. A comparison of the means using the Tukey HSD test showed that there was a statistically significant difference in both average and 85th percentile roundabout circulating speeds between the institutional and PB land use and the recreational, agricultural, residential, and industrial ones. The approach FFS had the strongest linear correlation with both the average and 85th percentile circulating speed. Entry width, exit width, and diameter exhibit a moderate correlation. Circulating width was found to have a weak relationship with the average circulating speed, and the entry angle had a weak negative linear relationship. The roundabout diameter had the greatest impact in predicting the average circulating speed, while entry width was the least important in predicting such speed. The average circulating speed model outperformed the 85th percentile speed model. The 85th percentile circulating speed model variables were the exit width and approach FFS. The predictors of land use, entry width, circulating width, entry angle, and diameter were omitted by the stepwise analysis, where the FFS of the approach had the highest impact in the 85th percentile circulating speed model.

Roundabouts are gaining significant attention worldwide as a safer and cost-effective intersection control alternative for low- to moderate-volume intersections. A roundabout's geometric design ensures travel speeds of roughly 50 km/h or less and provides additional safety for vehicles, bicycles, and pedestrians by its deflection angle [3]. Accordingly, roundabout crashes frequently occur at lower speeds and at less severe angles than those at other types of intersection control. Developing a prediction model for operational traffic speeds at roundabouts assists traffic agencies in selecting roundabout design features that can achieve specified operational speeds along roadways that are part of the traffic calming programs. Finally, the following recommendations are suggested:

- It is recommended to increase the entry deviation angle of existing roundabouts with higher entry speeds to improve their speed performance without affecting their capacities, while taking into consideration traffic safety.
- It is recommended to convert many light signals in Jordan into roundabouts because the latter reduce congestion and traffic accidents and volume.
- It is recommended to carry out more studies on other roundabouts in other cities in Jordan and other countries and compare the results with those of the present one.
- It is recommended to carry out studies that compare traffic accidents and congestion at roundabouts and light signals.

6. Declarations

6.1. Author Contributions

Conceptualization, B.A. and R.I.; methodology, M.M.; software, M.M.; validation, B.A., R.I., and A.S.; formal analysis, A.A.; investigation, A.S.; resources, M.M.; data curation, M.M.; writing—original draft preparation, M.M.; writing—review and editing, B.A. and A.S.; visualization, R.I.; supervision, B.A.; project administration, B.A. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

6.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

6.4. Conflicts of Interest

The authors declare no conflict of interest.

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