Modeling Through Traffic Speed at Roundabouts Along Urban and Suburban Street Arterials

by Bashar H. Al-Omari, Khalid A. Ghuzlan, and Lina B. Al-Helo

A total of 30 roundabouts with different dimensions and characteristics were selected from three cities in Jordan. The collected data included the approaching road free flow speed (FFS), area type, entry width, circulating roadway width, exit width, roundabout internal and external circle diameters, circulating roadway super elevation, entry deviation angle, and drive curve. The regression analysis showed that the entry width, internal circulating diameter, entry deviation angle, approaching FFS, and drive curve were significant in determining the average and 85th percentile roundabout circulating speed. The developed model was compared with other international models developed in the United States and Italy.

INTRODUCTION

Roundabout is used worldwide for controlling at-grade intersection traffic due to its low cost and effectiveness in traffic control (FHWA 2000). The modern roundabout is a type of circular intersection with channelized approaches, yield control at entries, and geometric curvature that slow entering vehicles (FHWA 2000).

In recent years, and with the rising traffic safety problem, traffic agencies showed more interest in applying traffic calming measures as part of their strategies to improve traffic safety levels. Roundabouts are one of the major physical traffic calming measures being used worldwide and have recently received more attention in many countries like the United States (TRB 2007).

This research aimed at quantifying the role of the roundabout as a traffic calming measure in reducing traffic speeds along urban and suburban street arterials by modeling the roundabout through traffic speed as a function of the geometric and operational characteristics of the roundabout and its upstream approaches (entry road links before the roundabout).

LITERATURE REVIEW

Speed represents a fundamental issue for road design and traffic engineering studies, and it is considered as the most important variable in roundabout geometric design (FHWA 2000).

Roundabout configuration forces drivers to slow down from the speed along the upstream highway (entry road link before the roundabout), stop or yield at the roundabout area, then accelerate to the speed along the downstream highway (exit road link after the roundabout), producing different speed profiles as compared with other types of intersection control or traffic calming devices (Margarida et al. 2006).

Drivers approaching a roundabout usually reduce their speeds to safely enter the roundabout and interact with other roundabout users. Their speed choice depends on several factors, including the upstream approach width, circulating roadway curvature (curve radius of the circulatory roadway around the roundabout), and traffic volumes at the roundabout entry and circulatory roadway (FHWA 2000). Antov et al. (2009) found that the midblock speed (speed at the middle of the road link before the roundabout) and the inscribed circle diameter (diameter of the circle formed by the outer edge of the road around the roundabout) affect the roundabout speed, and noticed that roundabout speeds are up to half of the midblock speeds. Montella et al. (2012) have identified the entry path radius (the radius of the curve formed by the vehicle path at the roundabout entry), deflection radius (the radius of the curve formed by the gradual shift in the vehicle path while moving from the road link to the roundabout), and deviation angle (the angle between the straight vehicle path before entering the roundabout and the tangent line of the curve formed by the vehicle path while entering the roadway) as the main parameters that control the roundabout speeds.

Some studies have used the following AASHTO (2011) horizontal curve (a curve in the plan location which connects two straight lines to change direction gradually) design equation for estimating the roundabout circulating speed as a function of the super elevation (the vertical distance between the heights of inner and outer edges of the roadway pavement), side friction factor (coefficient of friction in the perpendicular direction to the vehicle's movement that prevents the vehicle from sliding), and vehicle path radius (radius of curve formed by a vehicle path along the horizontal curve):

The circulating speed was determined using the following AASHTO (2011) equation;

(1) $V = \sqrt{(127\ R\ (e + f\ ))}$

Where:

V = predicted speed for circulating traffic movements (km/h),

R = radius of vehicle path (m).

e = super-elevation (m/m) (inner edge of curve is lower than the outer when e is positive).

f = side friction factor.

However, its application showed an overestimation in the through movement circulating speed of around 3-5 km/h (TRB 2007).

Bassani and Sacchi (2011) have developed the following empirical model in Italy for estimating the roundabout circulating speed as a function of the internal circle diameter (diameter of inner edge of the circulatory roadway around the roundabout), circulatory roadway width (the width of the circular road around the roundabout), and roundabout entry width (the width of the road at the point where entering vehicle path crosses the external circle diameter) with $R^2_{adj.} = 0.91$ & SEE= 2.2:

(2) $V_{85} = 0.4433\ D_{INT} + 0.8367\ W_{CR} + 3.2272\ W_{EL}$

Where:

V_{85} = 85-percentile operating speed at circulating roadway (km/h).

D_{INT} = diameter of the internal circle (m).

W_{CR} = width of the circulatory roadway (m).

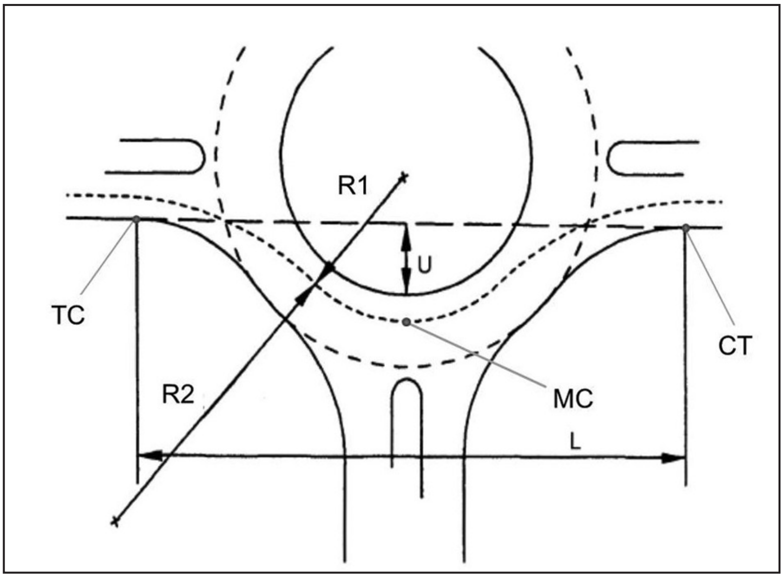
W_{EL} = width of the entry lane (m).

Chen et al. (2013) have evaluated roundabout safety utilizing the average approach speed (AAS), which was defined as the average of entry, circulating (moving around the roundabout), and exiting speeds. They estimated the AAS as a function of the average roundabout diameter (average of inscribed circle and central island diameters) and average roundabout roadway width (average of entry, circulating and exit widths). Hels and Orozova (2007) have noticed higher accident probabilities at roundabouts with larger drive curves that allow for higher driving speeds. They defined the drive curve (D) as a measure for through circulating path deflection (shift in the vehicle path while moving from the entry road link to the roundabout and then to the exit road link) over the length of the circulating path (road length inside the roundabout between points of entry and exit). It is calculated using the following equation:

(3) $$D = \frac{(0.25\ x\ L)^2 + (0.50\ x\ (U + 2))^2}{U + 2}$$

Where L, U, and other related parameters are shown in Figure 1 and defined as follows:

Figure 1: Definition of the Drive Curve



(Hels and Orozova 2007) with Modifications

D = the drive curve; which is a geometric characteristic that depends on the shift (U) and tangent distance (L)
U = the shift; which is the maximum horizontal distance between the imaginary line that represents the right side edge of the road assuming the roundabout does not exist to the left side edge of the circulating road around the roundabout at point MC
L = the tangent distance; which is the length of the straight imaginary line between points TC and CT
R1 = the internal radius of the assumed vehicle path along the circulating road
R2 = the external radius of the assumed vehicle path along the circulating road
TC = the point of transition from tangent to curve
CT = the point of transition from curve to tangent
MC = the middle point of the circulatory roadway along the vehicle path between the two points TC and CT

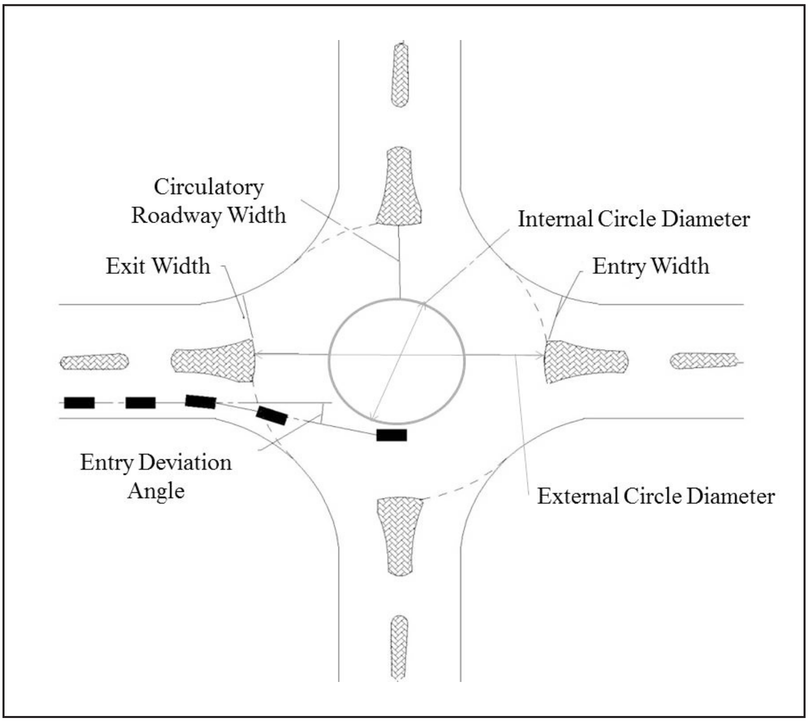
Daniels et al. (2011) found that the size of the central island does not affect the crash frequency, while the higher lateral deflection (lateral shift in the vehicle path while moving from the road link to the roundabout) at the roundabout entry tends to reduce the traffic speed, which is in agreement with Akçelik (2008).

DATA COLLECTION AND REDUCTION

A total of 30 roundabouts with different dimensions and characteristics were selected from the three major cities in Jordan: Amman, Zarqa, and Irbid (Al-Helo 2013). To avoid any bias in the collected data, the roundabouts were selected from locations with good pavement conditions, away from any upstream or downstream traffic calming measures or major traffic control devices, and with almost level and straight road alignments.

Geometric data were collected through field measurements during off peak periods, and included: roundabout external diameter (diameter of outer edge of the circulatory roadway around the roundabout), internal diameter, circulatory roadway width, entry width, exit width, entry deviation angle as shown in Figure 2, and the drive curve parameters (U, L, R) as shown in Figure 1.

Figure 2: Roundabout Geometric Elements



Also, field measurements were made for the circulatory roadway super-elevation (the vertical distance between the heights of inner and outer edges of the pavement for the circular road around the roundabout).

The speed data were collected using a laser radar gun during sunny days with dry pavement conditions and during times when there were no policemen in the area. Approaching street free flow speed (FFS) was measured at the midblock between the roundabout entry and the previous major traffic control device, or at 300m upstream of the entry, whichever is less. The roundabout circulating speed data were collected during off peak periods for the leading vehicles that have arrived at the roundabout entries when there were no conflicting vehicles present (free flow condition). The roundabout circulating speed data were measured for 100 through moving passenger cars at the middle of the circulatory roadway for each roundabout (point MC in Figure 1).

The sufficiency of the sample size was tested using equation (4) with acceptable errors (d) of 1, 3, and 5 km/h and confidence interval of 95% considering the actual speed standard deviation (S):

(4) $$N = [\frac{ZS}{d}]^2$$

Where:

N = Minimum sample size

Z = Number of standard deviations corresponding to the required confidence (1.96 for 95% confidence level)

S = Sample standard deviation (km/h)

d = limit of acceptable error in the average speed estimate (km/h)

It was found that the adopted sample size of 100 vehicles at each roundabout is higher than the required sample size for the three values of acceptable error (except for two roundabouts at 1 km/hour acceptable error). All roundabouts satisfied the required sample size at an acceptable error of 3 km/h, which is usually adopted in most traffic engineering studies. The terms used in this study are defined in Table 1 and a summary of the collected data characteristics are shown in Table 2.

Table 1: List of Variables Used in the Study

Variable	Symbol	Unit
Internal circle diameter[1]	D_i	m
External circle diameter[2]	D_e	m
Entry Width[3]	W_e	m
Circulatory roadway width[4]	W_c	m
Exit width[5]	W_x	m
Drive curve[6]	DC	m
Super Elevation[7]	SE	%
Entry deviation angle[8]	A_e	Radian
FFS of the upstream approach[9]	V_a	km/h
Area type[10]	AT	-

[1] Internal circle diameter = diameter of inner edge of the circulatory roadway around the roundabout.
[2] External circle diameter = diameter of the circle formed by the outer edge of the road around the roundabout.
[3] Entry Width = the width of the road at the point where arriving vehicles yield to circulating traffic then enter the roundabout.
[4] Circulatory roadway width = the width of the circular road around the roundabout.
[5] Exit width = the width of the road link after the roundabout at the point where vehicles exit the roundabout.
[6] Drive curve = geometric characteristic that depends on the shift, tangent distance, and vehicle path curve radius.
[7] Super Elevation = the vertical distance between the heights of inner and outer edges of the roadway pavement.
[8] Entry deviation angle = the angle between the straight vehicle path before entering the roundabout and the tangent line of the curve formed by the vehicle path while entering the roadway.
[9] FFS of the upstream approach = free flow speed of the entry road link before the roundabout.
[10] Area type = roundabout surrounding area type as urban or suburban.

Table 2: Characteristics of the Collected Data

Variable	W_e	W_c	W_x	D_e	D_i	DC	U	L	A_e	SE	V_a
Mean	6.6	6.73	7.33	47.4	34.37	42.1	10.6	76.5	0.31	0.25	52.0
Std. Dev	1.14	1.25	1.54	18.1	16.76	20.4	8.3	26.8	0.13	1.88	8.44
Min	4.0	4.50	5.00	18.7	9.67	18.3	00.0	35.0	0.10	-7.00	32.0
Max	9.7	10.00	11.50	87.0	70.00	95.0	29.0	151.0	0.54	4.32	67.0

ANALYSIS AND MODEL DEVELOPMENT

Regression analysis was used to estimate the roundabout circulating speed as a function of the main influencing geometric and operational factors, including upstream approach FFS, area type, entry width, entry deviation angle, circulatory roadway width, exit width, circulatory roadway super-elevation, drive curve, and external and internal diameters. Table 3 shows that the average and 85th percentile roundabout circulating speeds have high correlations (above $2/3^{rd}$) with the upstream approach FFS (0.79 and 0.75 respectively). Medium correlations (between $1/3^{rd}$ and $2/3^{rd}$) have occurred with the area type, entry width, internal diameter, external diameter, and drive curve, while low correlations (below 1/3rd) have occurred with the super elevation, circulatory roadway width, and deviation angle.

Table 3: Correlations of Variables with Average and 85th Percentile Circulating Speeds

Variable	Pearson Correlation	
	$V_{C,\,avg.}$	$V_{C,\,85th}$
Upstream Approach FFS (V_a)	0.788	0.749
Area type (AT*)	0.570	0.543
Internal Diameter (D_i)	0.511	0.396
External Diameter (D_e)	0.491	0.372
Entry Width (W_e)	0.530	0.481
Drive curve (DC)	0.426	0.523
Super-elevation (SE)	0.286	0.332
Circulatory Roadway Width (W_c)	0.196	0.090
Exit Width (W_x)	0.070	0.033
Deviation Angle (A_e)	-0.284	-0.399

*AT = 0 (Urban), 1 (Suburban)

The Stepwise regression method (Using the IBM SPSS Statistics 19 computer package) was used to select the most significant variables for estimating the average and 85th percentile roundabout circulating speeds producing the following two models:

(5) $V_{c,85th} = 14.321 + 0.196\,V_a + 0.655\,W_e + 0.11\,D_i + 0.048\,DC - 11.96\,A_e$

With $R^2 = 0.89$, $R^2_{adj} = 0.87$, and standard error of the estimate (SSE) = 1.39.

(6) $V_{c,\,avg.} = 11.098 + 0.183\,V_a + 0.645\,W_e + 0.11\,D_i + 0.027\,DC - 9.27\,A_e$

With $R^2 = 0.93$, $R^2_{adj} = 0.92$, and SSE = 0.95

Where: $V_{c,85th}$ = 85th percentile circulating speed (km/h)
$V_{c,\,avg.}$ = Average circulating speed (km/h)
V_a = Upstream approach FFS (km/h)
W_e = Entry width (meter)
D_i = Internal circle diameter (meter)
DC = Drive curve (meter)
A_e = Entry angle (radian)

Tables 4 and 5 show that the intercept, the variables and the regression model are all significant with 95% confidence interval. The distribution of the standardized residuals for the two models showed that they satisfy the normality assumption and consistency of variance, leading to significant relationships between dependent and independent variables with no need for any transformation.

Although the two models are significant (high R^2_{adj} and low SSE values), the average roundabout circulating speed model (R^2_{adj} = 0.92, SSE = 0.95) is stronger than the 85th percentile roundabout circulating speed model (R^2_{adj} = 0.87, SSE = 1.39) as it has higher R^2_{adj} and lower SSE values. This is because the average speed is more representative of different vehicles speeds and more sensitive to the effects of the influencing factors than the 85th percentile speed.

Table 4: Statistical Characteristics of Model 5

Source	Sum of Squares	Df	Mean Square	F	Sig.
Regression	377.094	5	75.419	38.524	.000
Residual	46.985	24	1.958		
Total	424.078	29			
R^2 = 0.889, R^2_{adj} = 0.866, and SSE = 1.39					
Variables	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	14.321	2.312		6.193	0.000
W_e	0.655	0.251	0.198	2.606	0.016
D_i	0.107	0.020	0.467	5.490	0.000
DC	0.048	0.016	0.238	2.963	0.007
V_a	0.196	0.037	0.434	5.322	0.000
A_e	-11.964	2.915	-0.400	-4.104	0.000

Table 5: Statistical Characteristic of Model 6

Source	Sum of Squares	Df	Mean Square	F	Sig.
Regression	297.347	5	59.469	61.067	.0000
Residual	23.372	24	.974		
Total	320.719	29			
R^2= 0.931 and R^2_{adj} = 0.917 and SSE=0.95					
Variable	Unstandardized Coefficients		Standardized Coef-ficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	11.098	1.631		6.805	0.000
W_e	.645	.177	.224	3.640	0.001
D_i	.110	.014	.548	7.941	0.000
DC	.027	.011	.155	2.374	0.026
V_a	.183	.026	.465	7.028	0.000
A_e	-9.268	2.056	-.356	-4.507	0.000

These models are consistent with the Bassani and Sacchi (2011) model in terms of estimating the roundabout circulating speed as a function of the internal circle diameter and entry width. However, the circulatory roadway width was included in the Bassani and Sacchi (2011) model, while it is replaced by the upstream approach free flow speed, drive curve, and entry angle in this study's models.

The average and 85th percentile roundabout circulating speeds are directly proportional to the upstream approach free flow speed, entry width, internal circle diameter, and drive curve, while they are inversely proportional with the entry angle.

The area type was not significant in the two models as its effect is already considered in the upstream approach free flow speed. Suburban streets usually have higher free flow speeds than urban streets.

As entry width increases, drivers can have more flexibility in choosing their path while entering the roundabout such that they can keep higher speeds, especially during low traffic volume and free flow conditions. Also, increasing the entry width reduces the deflection (horizontal deviation in the vehicle movement at entry due to entry curvature) imposed on vehicles at entry which allow for lower curvature that reduces the side friction with adjacent objects at the entry (Margarida et al. 2006). The exit width was not significant in the model because it is located downstream of the circulatory roadway midpoint, where speed measurements were conducted.

Increasing the drive curve reduces the curvature in the driver's path inside the roundabout, which results in an increase in the circulating speed. This is consistent with the Hels and Orozova (2007) study, which found that roundabouts with larger drive curves had higher driving speeds.

The entry deviation angle is inversely proportional with circulating speed, which is in agreement with Daniels et al. (2011). This is expected as increasing entry curvature increases entry angle and leads to a decrease in the entry speed (Montella et al. 2012).

The size of the internal circle diameter has a significant effect on the circulating speed, as it determines the curvature of the driver's path, which in turn determines the speed at which drivers can travel along the roundabout circulating roadway. This is consistent with the AASHTO (2011) horizontal curve design equation and the Bassani and Sacchi (2011) models. The roundabout external diameter was not significant in the models because drivers tend to move along the left side of the circulating roadway to reduce the curvature effect and keep relatively higher speeds; so the internal diameter was more important than the external diameter. The circulatory roadway width was also not significant in the models because it has more influence on the roundabout capacity rather than circulating speed. Furthermore, the circulatory roadway super-elevation was not significant in the models because not much variability was observed in this factor between the selected roundabouts for this study.

COMPARISON WITH OTHER MODELS

Comparisons were made between the proposed model in this study with the predictions based on Bassani & Sacchi (2011) and AASHTO (2011) models.

In order to estimate the circulating speed using the AASHTO (2011) equation (1), the vehicle path radius while circulating was assumed equal to the internal circle radius plus 1.5 m as recommended by TRB (2007). The super-elevation was measured from the field using the Level surveying instrument. The side friction factor was estimated as a function of speed using the AASHTO (2011) design charts. The estimated side friction values were in the range of (0.25-0.35) corresponding to speed values of (20 to 37) km/h.

In using the Bassani & Sacchi (2011) model, the required geometric parameters are the entry and circulatory roadway widths and the internal circle diameter that were collected from the field in this study for all roundabouts.

Both AASHTO (2011) and Bassani & Sacchi (2011) models were applied to this study's roundabouts based on the collected field data, and the predicted circulatory speed results were plotted against the observed data as shown in Figures 3 and 4. It can be seen that the roundabout circulating speed values are underestimated by the AASHTO (2011) equation and overestimated by the Bassani and Sacchi (2011) model. The developed models in this study have shown much better estimations for the measured roundabout circulating speed values as shown in Figures 5 and 6.

The paired t-test was used to check if the differences between the actual and predicted circulating speed are significantly far from zero. Table 6 shows that, with 95% confidence, there are significant statistical differences between the actual and predicted circulating speed by the AASHTO (2011) model (mean of 7.38 km/h, standard deviation of 5.41, t-ratio of 7.47, and P-value < 0.05) and Bassani & Sacchi (2011) model (mean of -10.52 km/h, standard deviation of 8.32, t-ratio of - 6.93, and P-value < 0.05). Thus, the hypothesis that the deviations are equal to zero is rejected for the two models.

Figure 3: AASHTO (2011) Equation Predictions vs Measured 85th Roundabout Circulating Speeds

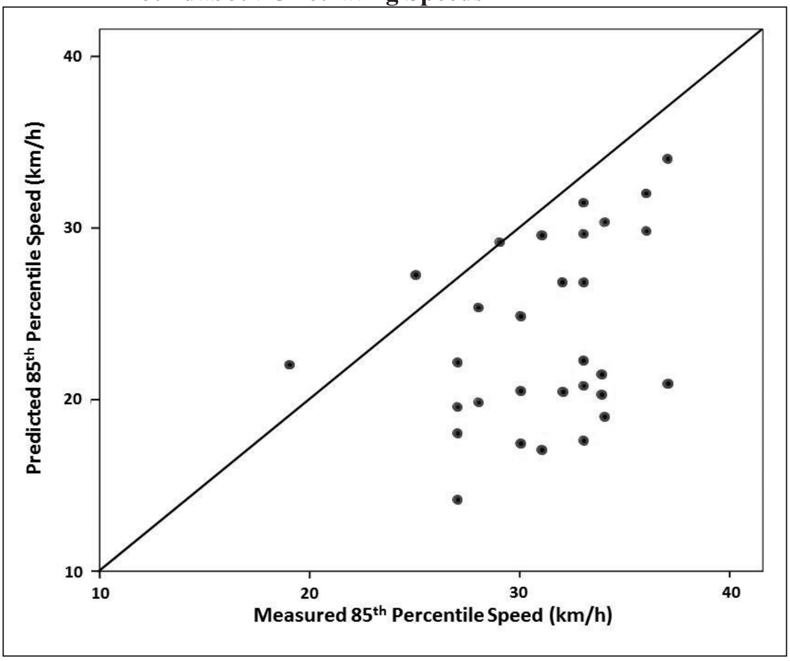


Figure 4: Bassani & Sacchi (2011) Model Predictions vs Measured 85th Roundabout Circulating Speeds

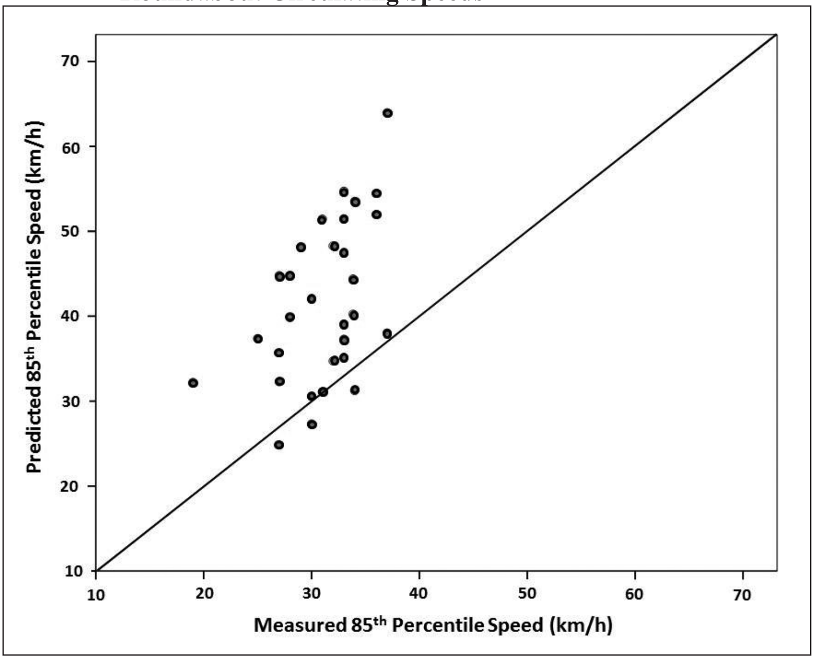


Figure 5: Proposed Model (Model 5) Predictions vs Measured 85th Roundabout Circulating Speeds

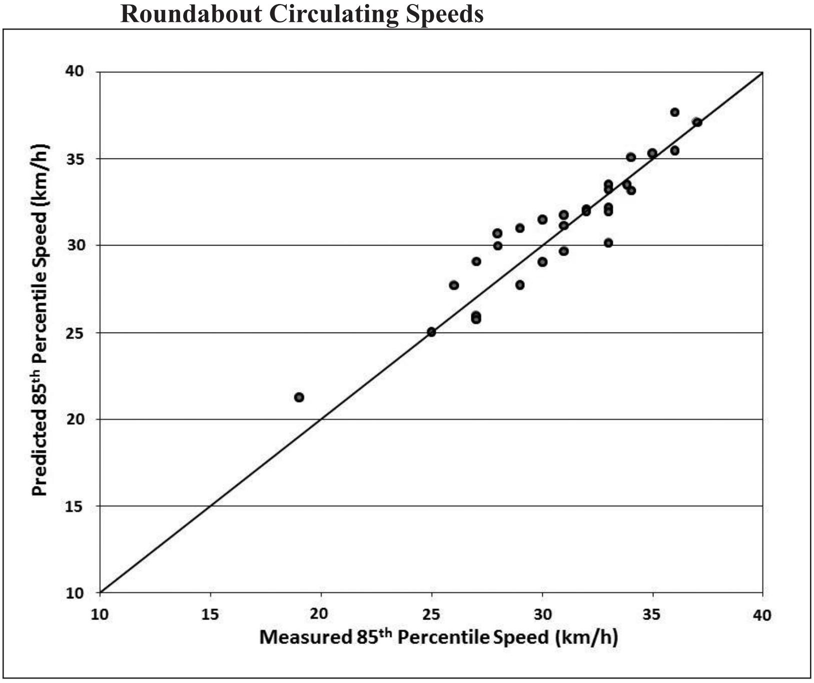


Figure 6: Proposed Model (Model 6) Predictions vs Measured Average Roundabout Circulating Speeds

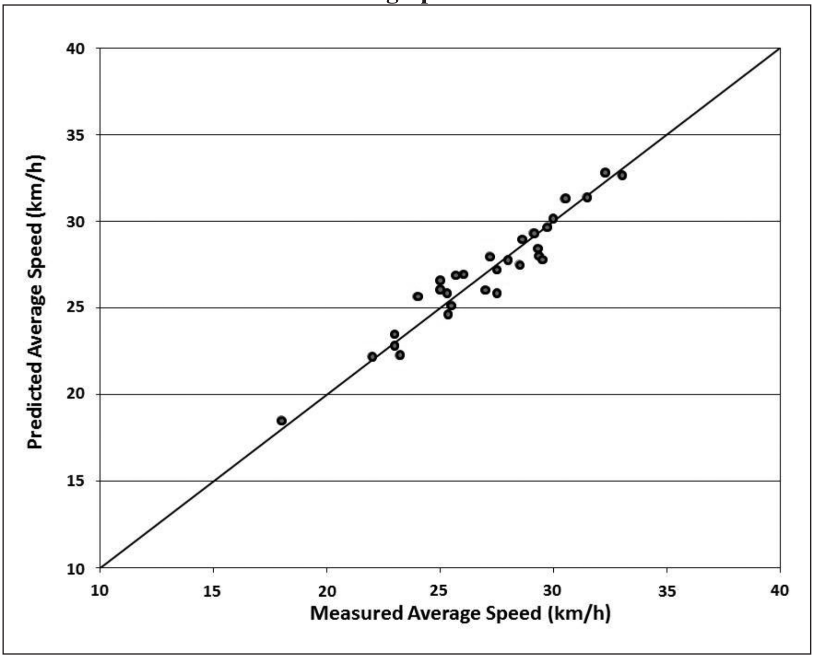


Table 6: Paired t-Test for Comparing the Developed Model with AASHTO (2011) and Bassani & Sacchi (2011) Models

Pairs	Mean	ST. DEV	SE. MEAN	T	P-value
Observed Vs. Predicted by AASHTO Model	7.38	5.41	0.99	7.47	0.000
Observed Vs. Predicted by Bassani & Sacchi Model	-10.52	8.32	1.52	-6.93	0.000

The measured circulating speeds were also regressed against the computed values using the AASHTO (2011) and Bassani & Sacchi (2011) models. The results showed R^2 of 13.5 % and SEE of 3.77 for the AASHTO (2011) model, and R^2 of 25.5 % and SEE of 3.50 for the Bassani & Sacchi (2011) model. The developed models in this study have much higher R^2_{adj} and lower SSE values; (R^2_{adj} = 0.866, SSE = 1.39) for model 5 and (R^2_{adj} = 0.917, SSE = 0.95) for model 6.

These differences may refer to the fact that these models did not consider all the influencing factors in addition to the differences in driver behavior between developed and developing countries.

SUMMARY AND CONCLUSIONS

This study aimed at quantifying the roundabout's role as a traffic calming measure in reducing traffic speeds along urban and suburban street arterials by modeling the through traffic speed at the middle points of the roundabout's circulatory roadways as a function of the geometric and operational characteristics of roundabouts and their upstream approaches.

Field data were collected from 30 roundabouts with different dimensions and characteristics, selected from three major cities in Jordan: Amman, Zarqa, and Irbid. The collected data included the approaching street free flow speed, area type, entry width, circulating roadway width, exit width, roundabout internal and external circle diameters, circulating roadway super elevation, entry deviation angle, and drive curve.

Based on the regression analysis, it was found that the roundabout circulating speed is mainly dependent on the approaching street free flow speed, internal circle diameter, entry deviation angle, entry width, and drive curve. The circulating speed is inversely proportional with the entry deviation angle, while it is directly proportional with all other variables. This implies that roundabouts' traffic operating speeds can be reduced by increasing the entry deviation angle or reducing the approaching street free flow speed, internal circle diameter, entry width, and drive curve. The average circulating speed model was found to be better than the 85th percentile speed model. It is recommended that traffic engineers use the average circulating speed model to get more accurate estimates for the roundabouts' operating speeds.

Significant differences were found between the measured roundabout circulating speeds and their corresponding predicted values by the AASHTO (2011) equation and Bassani & Sacchi (2011) model. These differences may refer to the fact that these models did not consider all the influencing factors in addition to the differences in driver behavior between developed and developing countries.

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