An analysis on impact of geometric elements of multilane roundabouts on driver behavior

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ABSTRACT

The design of the geometry of a roundabout involves choosing between trade-offs of safety and capacity. A well-designed roundabout operates most safely when its geometry forces vehicles to enter and circulate at slow speeds, achieving a smooth speed profile by requiring vehicles to negotiate the roundabout along a curved path. According to FHWA publication *Roundabouts: An Informational Guide*, the fastest path modeling is a critical component of safe roundabout design. As the construction of roundabouts is quite new in Greece, the driver behavior entering a roundabout is required to be investigated. This paper presents the results of experimental research that has been conducted as a first step in the development of a vehicle speed model for roundabouts in Greece. The research aims to define the basic path elements of vehicle movement in the roundabout at which the maximum speed is achieved. To address this need, a detailed analysis of actual field-measured speeds was carried out on a sample of 6 straight directions through multilane roundabouts in Greece, characterized by different geometric elements. Roundabouts' performance was recorded with the use of an Unmanned Aerial Vehicle during free flow conditions on weekdays. Trajectories and kinematic characteristics of the vehicles were extracted. Measured speeds along the curved paths were compared to the predicted speeds that USA guidelines define. The findings from the study show a significant difference between actual and predicted speeds and a strong correlation between speed and design elements.

Keywords: Roundabouts, Geometric design, Fastest path, Traffic safety, UAV, Vehicle speed

INTRODUCTION

Roundabouts are an increasingly appealing alternative form of at-grade intersections because of their multiple advantages regarding traffic safety, operational efficiency, atmospheric emissions and aesthetics (*1*). Due to this fact, in the last decades roundabouts have gained increased political acceptance worldwide and are now a viable alternative for intersection design.

Their implementation on a road network is a solution in cases where problems regarding traffic safety or capacity occur. Roundabouts are statistically safer for motorists than other at-grade intersections because of lower vehicle speeds, reduced crash angles and fewer conflict points. Before-and-after studies of roundabout conversions indicate that modern roundabouts are safer than previous intersection treatments (*2*,*3*). However, the most important reason that nowadays roundabouts have been a widespread design solution, is their effectiveness to road safety by the reduction of the number of road fatalities (*1*,*4*).

The design of the geometry of a roundabout involves choosing between trade-offs of safety and capacity. The appropriate selection of the geometric parameters for the roundabouts design can enhance the operational performance and traffic safety. A well-designed roundabout operates most safely when its geometry forces vehicles to enter and circulate at slow speeds, achieving a smooth speed profile by requiring vehicles to negotiate the roundabout along a curved path. According to this, the vehicle speed through a roundabout is one of the most important parameters in the design of a roundabout.

Research on the influence of roundabouts' design elements on operational and safety efficiency is still in its beginning in Greece. According to FHWA publication (*5*), the fastest path modeling is a critical component of safe roundabout design. As the construction of roundabouts is quite new in Greece, it is required the driver behavior of roundabouts users to be investigated.

RESEARCH OBJECTIVE

A knowledge of vehicle trajectories and speeds is considered necessary when the geometric layout of a roundabout is designed. Designers use swept path of turn simulation software and speed prediction models. Actual vehicle trajectories and speeds directly recorded at a newly constructed roundabout can confirm whether the design assumptions are valid (*6*).

This paper presents the results of a first step in the development of a model for operating speed at roundabouts in Greece. The research aims to define the basic path elements of vehicle through movement in a roundabout at which the maximum speed is achieved. To address this need, a detailed analysis of actual field-measured speeds was conducted on a sample of 6 straight directions through multilane roundabouts in Greece, characterized by different geometric elements.

LITERATURE REVIEW

Many studies indicate that speed is a fundamental issue for roundabout geometric design (*5*). According to many researchers, speed distribution related to geometric features (e.g., entry curvature, entry path radius, entry width, central island diameter) can be used as a measure of safety level for roundabouts *(4, 6–8)*. The difference between design and operational speed is required to be the minimum to ensure predictable movements from drivers. Several studies show that the observed speeds of vehicles significantly differ from the predictable speeds (*9,10)*.

Surdonja et al., *(11)* compared measured speeds at single lane roundabouts with calculated speeds according to existing models that predict speeds at roundabouts. Results showed that the measured speeds are lower than the speeds obtained by calculation for all cases. Pilko et al., (*12*) compared actual speeds against design speeds at four Croatian roundabouts. Results showed correlation between the design speeds and the actual observed speeds. However, the deviations between them were evident (from -46% to +13%). Similar speed comparisons were conducted on *(13)*. Results presented new relationships between circulating operating speeds and geometric features of Italian roundabouts and confirmed the significant overestimations of current prediction models. An empirical speed model for estimating the roundabout circulating speed was developed based on actual measured speeds on *(14)* as well.

Estimation of Maximum Speeds at Roundabouts

A well-designed roundabout operates most safely when its geometry forces to reduced vehicular speeds. The vehicle path curvature is a major parameter being considered for an appropriate design of roundabouts in terms of road capacity and traffic safety. Studies have shown that the increase of vehicle path curvature has a positive effect on vehicle crash rates, as the relative speed between entering and circulating vehicles is decreased (*5*). However, in the case of multilane roundabouts, an increase in vehicle trajectory curvature causes an increase in the side friction between the road lanes, which can result in vehicle path overlap and higher potential for traffic accidents (*15*). Therefore, an optimum design speed is recommended for each roundabout category. The recommended maximum theoretical entry design speed for vehicles entering the various types of roundabouts is presented in the following table (*1*):

Table 1 Recommended maximum entry design speeds (*1*)

Roundabout Type	Recommended maximum theoretical entry design speed
Mini roundabout	30 km/h
Single-lane roundabout	40 km/h
Multilane roundabout	40 to 50 km/h

The determination of roundabout design speed is related to the curvatures of vehicle paths through a roundabout. The formation of the vehicle paths at roundabouts varies according to models and guidelines the different countries use. The CROW *(16)* model is being used at the Dutch, Slovenian, Serbian and Croatian guidelines and depends on geometric elements of the roundabout. The FHWA model is being used at the American guidelines *(1)* and requires the determination of maximum allowable (fastest) vehicle paths for all allowed directions of movement in the roundabout. Finally, the Australian and UK guidelines *(17–18)* use a similar methodology to American guidelines. However, only the straight movement through the roundabout is considered.

As the determination of vehicle speeds at roundabouts in Greece, that the Greek draft guide OMOE-K3 presents, is based on the American practices and guides, the FHWA approach was used for the purposes of the study (*19*).

According to the FHWA approach (*1*), the process of the determination of vehicle speeds on roundabouts, requires the drawing of the fastest paths allowed by the geometry for all possible directions of movements (**Figure 1)**. The fastest path is defined as "*the smoothest, flattest path possible for a single vehicle, in the absence of other traffic and ignoring all lane markings, traversing through the entry, around the central island, and out the exit*".

Five critical path radii are checked for each approach. The entry path radius (R_1), the circulating path radius (R_2), the exit path radius (R_3), the left-turn path radius (R_4) and the right-turn path radius (R_5). The minimum path radius along the critical path radii of the fastest paths is used for the calculation of vehicles speeds.

An objective and reliable fastest path is comprised of a series of consecutive reverse spiral curves that are tangent to each other *(1,4)*. The short length of tangent reflects the time it takes for a driver to turn the steering wheel. There are two main drawing techniques: (a) the freehand and (b) the computer-aided technique *(1)*. In the first case, the engineer draws by hand a natural representation of the way a driver negotiates the roundabout on scaled drawing of the intersection. This method reflects better the anticipated driving behavior. However, requires high skills and expertise while it is difficult to use on the design process and thus is discouraged. On the other hand, the computer-aided technique is based on drafting software (CAD) and is mainly carried out by two methods: (a) the cubic splines technique or Wisconsin method *(20)* and (b) tangent reserve curves (arcs) technique or ACHD method *(21)*.

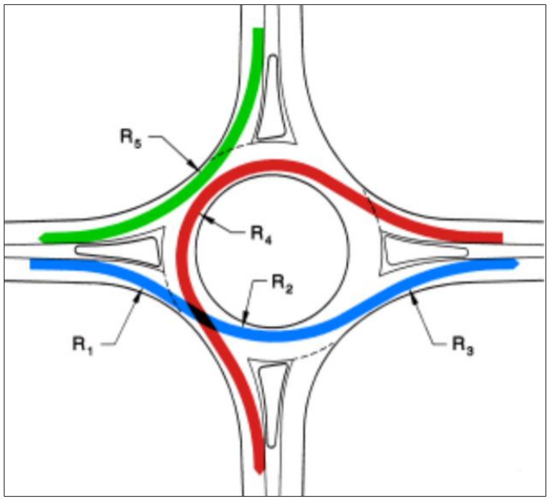

Figure 1 Vehicle path radii (*5*)

Theoretical fastest paths of through movements were drawn for the selected multilane roundabouts by using a CAD tool according to the proposed method of *(20)*. The application of this method is proposed by the US guidelines *(1)*. The design of the fastest paths and calculation of radii was followed by the calculation of the expected operating speeds of vehicles on the path according to **Equation 1.**

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

where, R is the corresponding radius, e is the superelevation and f is the friction coefficient between the wheel and the pavement.

The most common superelevation values (e) are +0.02 and -0.02 which corresponds to 2% cross slope. According to (5), it is usually assumed entry and exit curves (R_1 and R_3) to have the superelevation value of +0.02 and the curves around the central island (R_2) to have the -0.02.

According to Equation 1, vehicles' speeds in respect of path radii can be calculated. Specifically, the values of entry speed (V_{1p}), through-movement circulating speed (V_{2p}), though-movement exit speed (V_{3p}) and left/right turn-movement circulating speed (V_{4p} and V_{5p}) are estimated according and used for the design process of the roundabout.

To better predict actual entry and exit speeds, US guidelines *(1)* recommend the use of the **Equation 2** and **Equation 3,** respectively. This is meaningful especially when radius path is large or nearly tangential and a reasonable vehicle speed can not be determined.

$$V_{1p} = min\left(\frac{V_{1pbase}}{3.6\sqrt{\left(\left(\frac{V_{2p}}{3.6}\right)^2 + 2a_{12}d_{12}}}\right) \qquad (2), \qquad V_{3p} = min\left(\frac{V_{3pbase}}{3.6\sqrt{\left(\left(\frac{V_{2p}}{3.6}\right)^2 + 2a_{23}d_{23}}}\right) \qquad (3)$$

where, V_{1pbase} and V_{2pbase} are V_{1p} and V_{3p} speeds respectively, predicted based on path radius. V_{2p} is the circulating speed predicted based on path radius, a_{12} (=1.3 m/s2) and a_{23} (=2.1 m/s2) represent deceleration/acceleration between the midpoint of V_2 path and the point of interest along V_1 and V_3 path respectively, and finally, d_{12} and d_{23} represent the distance along the vehicle path between the midpoint of V_2 path and the point of interest along V_1 and V_3 path, respectively.

The consistency between the speeds must be checked per each movement to achieve high levels of traffic safety. Speed control that is provided by the geometric features (such as the path radius) contributes to the minimization of the relative speeds between conflicting traffic streams and the optimization of entry capacity due to reduced critical gaps. Generally, the entry path radius (R_1) should be smaller than the circulating path radius (R_2), which in turn should be smaller than the exit path radius (R_3). However, in some circumstances, it is acceptable the value of R_1 to be greater than R_2. In these cases, the relative difference in entry speed (V_{1p}) and through-movement circulating speed (V_{2p}) must be less than 20 km/h (*1,5*).

METHODOLOGY

Site Selection and Survey Equipment

The selection of the proper roundabouts for the analysis was based on the following criteria, in accordance with the location and design elements of the intersections:

- Roundabouts are located near the urban limits of the city.
- Roundabouts have been designed recently (2019) according to Greek design standards.
- The geometric elements of the roundabouts differ from one another.
- The angle between approach legs of through movements is close to 180° for the two roundabouts, while on the other roundabout the angle differs.
- Both roundabouts are not located on restricted areas (no-fly zones) regarding UAV surveys.

The case study roundabouts located in the cities of Larissa and Thessaloniki were selected for the purposes of the study. It is about three suburban multilane roundabouts constructed recently in Greece, relied on different geometric features.

Two types of equipment were selected to acquire reliable vehicle speeds data and geometric elements of the selected roundabouts: (a) a quadcopter UAV and (b) a RTK GNSS receiver. The selected UAV can capture videos up to C4K analysis with a frame rate of 60 fps and high-resolution images (5472x3078). The RTK GNSS receiver that was used provides reliable and high-accuracy data collection. The position of selected GCPs can be determined in centimeter-level accuracy in real world conditions. Specifically, the accuracy of this equipment for examined of survey is 8mm+1ppm (horizontal) and 15mm+1ppm (vertical).

UAVs are recently being used in transportation field to monitor and analyze the traffic flow *(22)*. There are many benefits regarding traffic data acquisition that this method offers. It is highlighted that by this method, the driver's attitude is not distracted by the equipment, as the camera is in the air (*23*). According to this, speed profiles and trajectories of vehicles are not affected by this type of survey. However, there are many factors as well that influence the performance of this process. Among them, weather conditions (e.g., rain), technical issues (e.g., low battery duration) and regulatory issues (e.g., no-fly zones) are the most critical to be mentioned (*22*).

Survey Execution

Roundabouts' performance was recorded with the use of the Unmanned Aerial Vehicle (UAV) during summer and autumn of 2019. Two types of data were collected in this experiment; (a) data relies on the geometric elements of the roundabout and (b) data regarding the kinematic characteristics of the vehicles.

Field measurements were selected to be conducted during of-peak periods to ensure free flow speed conditions. Real vehicles speeds in unobstructed traffic conditions were collected. Moreover, weather conditions were stable and did not affect the vehicle movements.

Data Acquisition by using Unmanned Aerial Vehicles

The geometric features of the roundabouts were measured on CAD software by digitizing georeferenced frames, following the methodology that is extensively described in (*23*). A brief overview of the whole process is described below.

- Firstly, numerous homogeneously distributed characteristic natural ground control points (GCPs) (such as corners of manholes and tactile pavements, intersections of white pavement markings, etc.) were identified in the areas of interest. The use of natural GCPs has the advantage of the flexibility to conduct surveys over different periods of time *(22)*. The collection of high-accuracy GNSS coordinates of the GCPs (horizontal position and altitude coordinate) was conducted using GNSS RTK data collection on the field. The selected geographic reference was the "GGRS87/ Greek Grid".

- High-resolution images (4096x2160) were acquired using a UAV in specific flight altitude and vertical viewing angle. Recordings of a nadir point of view are required to minimize camera errors.
- The acquired images were georeferenced in high accuracy using an open-source GIS software (QuantumGIS) *(24)*. A digitization process was conducted regarding the geometric elements of the roundabouts.

The final values of roundabouts' geometric features are presented in **Table 2**.

Table 2 Geometric elements of case study roundabouts

Site	Roundabout A				Roundabout B		Roundabout C	
Location	39°38'00.5"N 22°23'03.5"E				39°38'11.5"N 22°24'02.5"E		40°33'10.6"N 23°01'02.0"E	
Number of legs	4-leg				3-leg		4-leg	
Inscribed circle diameter (m)	56				56		36	
Circulating roadway width (m)	10				10		6.5	
Truck apron width (m)	2				2		-	
Approach leg	East *(1)*	South *(2)*	West *(3)*	North *(4)*	North *(1)*	South *(3)*	NE *(1)*	*SW (3)*
Entry width (m)	7.8	7.4	7.4	7.6	8.9	8.7	5.6	6.0
Exit width (m)	8.0	5.2	7.9	7.6	8.8	8.8	5.6	6.1
Entry radius (m)	26.9	19.8	20.5	20.9	28.6	29.8	10.0	10.5
Exit radius (m)	21.2	23.5	29.2	32.9	15.1	28.4	26.2	24.7
Through movements	1→3	2→4	3→1	4→2	1→3		1→3	
Angle between legs (°)	179	175	181	185	226		191	

According to the existing literature, many studies that have been recently conducted are dealing with traffic data acquirement through unmanned aerial vehicles *(22, 23, 25–29)*. The methodology that is used in these studies can be divided into three categories regarding the video processing technique that is used: a) the manually process, b) the semi-automatic process and b) the automatic process. The first two methods are more accurate, however, are time-consuming. On the other hand, the third method promises quicker results by using detection techniques and tracking algorithms.

A manually method was used in this study for the speed data acquirement by the UAV. Following the process described above regarding the measurement of the geometric elements of roundabouts, video frames were analyzed as well. The software QGIS *(24)* was used for the extraction of the kinematic characteristics of vehicles. A calibration procedure for the preparation of traffic data acquirement was necessary. Firstly, a stabilization procedure was followed *(30)*. Video frames were extracted and were georeferenced for each examined video per 0.033 sec intervals (fps: 29.97). Trajectories of vehicles were extracted for specific events (at the entrance, the exit and in the middle of the roundabout for through movements). Specifically, the center of the front bumper of each vehicle was identified and the coordinates were extracted. Speeds were calculated as derivatives of the positions with respect to time. The total sample of the analyzed vehicle speeds corresponds to 30 vehicles per each through movement. The density of the extracted trajectories of vehicles on though movements at free flow speed conditions at Roundabout A (straight direction 1-3) is presented in the following figure.

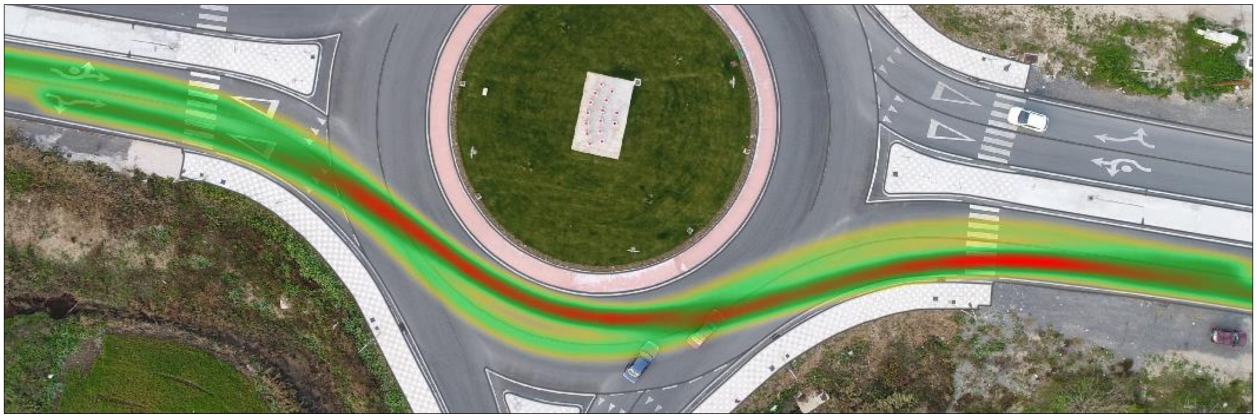

Figure 2 Density of extracted vehicle trajectories

It is noted that by this method valuable data regarding the kinematic characteristics and the drivers' behavior can be extracted and used for further analysis. The accuracy of vehicle speeds regarding this method was calculated to be less than 1 km/h as the georeferencing procedure provided low values of RMSEs.

In **Figure 3** the position of calculated actual vehicle speeds at the entrance, the exit and in the middle of Roundabout A are presented.

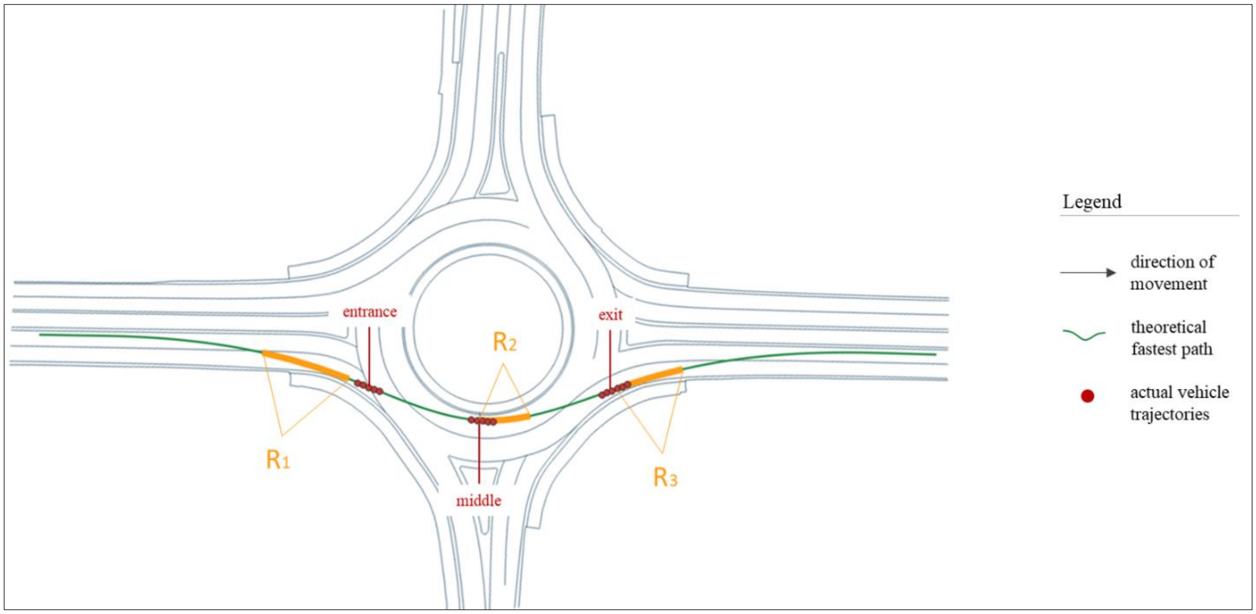

Figure 3 The location of calculated vehicle speeds on Roundabout A

The designed fastest path of the through movement 1-3 gives a graphically view of the relation between analyzed actual vehicle trajectories and constructed fastest path that was used for the calculation of the design speed. Moreover, path radii used for the prediction of vehicles' speeds are presented as well.

Maximum Vehicles Path Speed Analysis

Theoretical fastest paths of the multilane roundabouts were drawn by using a CAD method according to the proposed method of *(20)*. Specifically, UAV calibrated frames of the roundabouts according to the process that was mentioned before, were used for the analysis. Geometric features and road markings were drawn. The properly offsets regarding the selected approach were determined and finally the theoretical fastest paths of the three multilane roundabouts were drawn. Specifically, according to (*1*), the path is drawn assuming that the wide of vehicles is 1.8 m. The vehicle path was constructed beginning 50 m upstream of the yield line and following the defined limits regarding the offsets to geometric elements of the roundabouts:

a. 1.5 meters from concrete curbing, splitter islands and roadway centerline.
b. 1.0 meters from a painted edge line.

The entry path radius (R_1), the circulating path radius (R_2) and the exit path radius (R_3) were calculated for the examined through movements by measuring the minimum radii of fitted arcs on proper portions of the constructed fastest paths. In case of the entry path radius (R_1), the length of the fitted arc per each through movement was at least 20 m (*1*). According to the previous equations and path radii measurements, the operating speeds were estimated for the three case studies.

The following Figure and Table present the constructed fastest paths and the measured radii for the analyzed roundabouts.

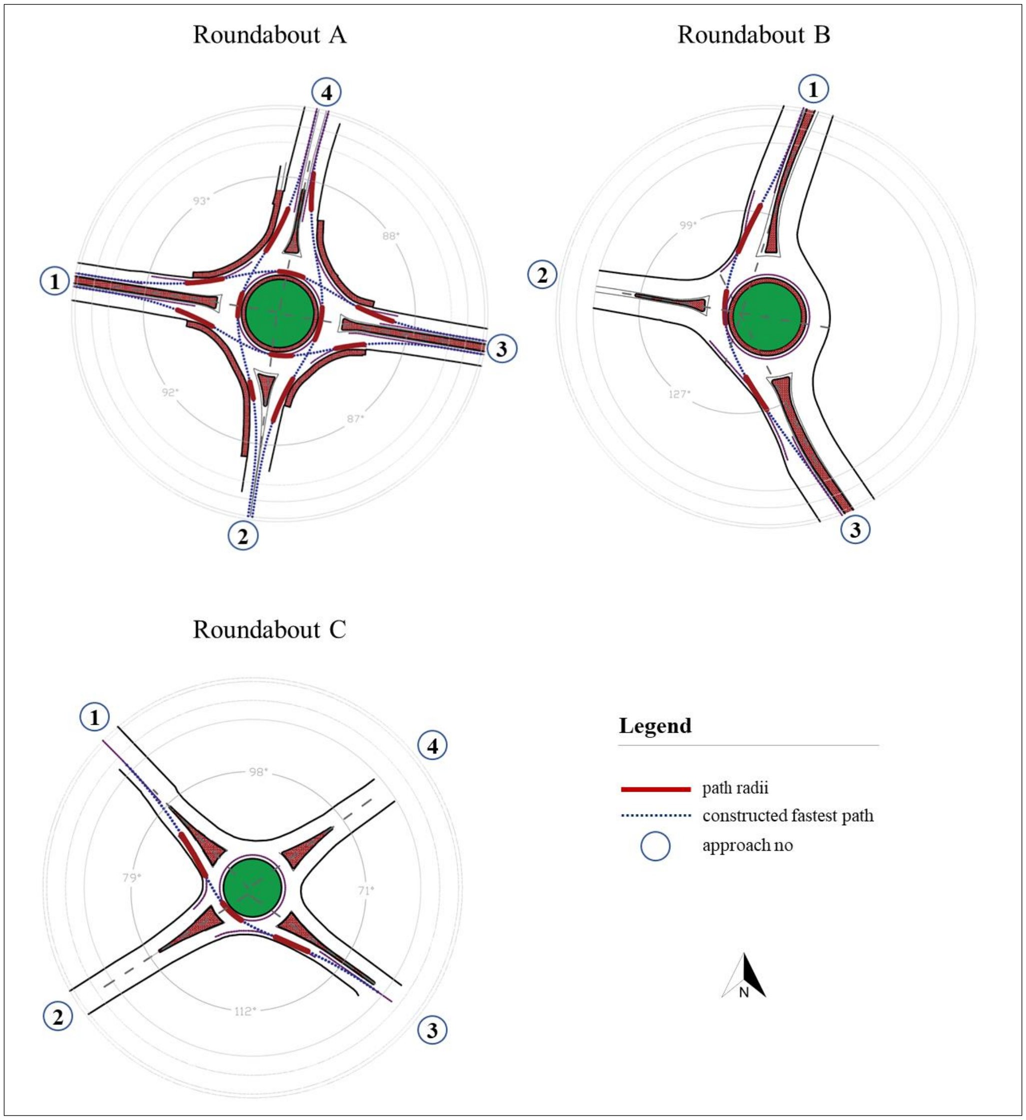

Figure 4 Constructed fastest paths

Table 3 Calculated values of path radii and design speeds

Roundabout	Through Movement	Path Radius (m)			Transitions (m)		Calculated design speed (km/h)		
		R_1	R_2	R_3	d_{12}	d_{23}	V_1	V_2	V_3
A	1 – 3	119.0	38.2	120.2	43.3	36.3	50.4	32.8	55.3
	4 – 2	117.9	31.6	101.5	42.0	41.6	48.5	30.6	52.1
	2 – 4	106.1	38.3	110.3	37.0	45.2	48.2	32.9	53.9
	3 – 1	116.7	34.4	121.0	37.0	43.7	47.4	31.6	55.8
B	1 – 3	226.4	49.3	233.7	36.4	60.9	50.3	36.1	68.0
C	1 – 3	211.8	29.5	297.8	27.3	25.9	42.5	29.9	48.0

According to **Table 3**, it can be observed that the entry and exit path radii of Roundabout A range around similar values concerning the different through movements. In contrast, the entry and exit path radii of Roundabouts B and C range at high values. In almost all cases, the design entry speed is calculated to be close to the recommended maximum value of 50 km/h. It is highlighted, that the entry speed for all cases was calculated based on V_{2p} speed (Equation 2), as it was observed to be the minimum one. In the cases of Roundabout B and C, entry path radii were large enough to determine acceptable vehicle speeds.

The calculated speeds of Roundabout B are extremely high, which is probably due to the high value of the angle between the two legs of the through movement (226º). According to (*1*), roundabouts with large angles between legs are difficult to provide adequate deflection. As a result, it is possible for these roundabouts to be characterized by high vehicle speeds. The roundabout B confirms this fact, while the designed fastest path of the through movement leads to reduced safety performance.

Analysis of the speed results included the determination of the V_{85} speed of vehicles at the entrance of the roundabouts, in the middle of the roundabouts and at the exit of the roundabouts. Through movements were only considered. The predicted values of entry speed (V_{1p}), through-movement circulating speed (V_{2p}) and though-movement exit speed (V_{3p}) were calculated using Equations 1, 2 and 3. The 85th percentile speed determines the speed of the drivers that negotiate roundabouts choosing fast paths. Recommended equations of US guidelines provide both actual estimated speeds (equations based on acceleration/deceleration effect) and speeds that can be adopted by the fastest driver (largest path radii). According to this, observed speeds and that derived from US guidelines may differ, but they are comparable *(13).*

EVALUATION FRAMEWORK AND RESULTS

The normality of data distribution for each case was examined by the Kolmogorov-Smirnov (K-S) test (31). Results (p>0.05) confirm the assumption of normal distribution. Therefore, Pearson correlation was applied to investigate the correlation between the variables. The following table presents the correlations between 85th percentile operating observed speed at the entrance, in the middle and at the exit of the roundabouts and selected geometric features of the roundabouts.

Table 4 Bivariate Correlation Analysis Results

Variables	Pearson Correlations		
	Entry speed - $V_{1,85}$	Circulating speed - $V_{2,85}$	Exit speed - $V_{3,85}$
1. Entry width	0.923^{**}	0.952^{**}	0.911^{*}
2. Exit width	0.442	0.465	0.353
3. Entry radius	0.867^{*}	0.935^{**}	0.918^{**}
4. Exit radius	0.143	0.357	0.363

values along with "**" are significant at 0.01 level and values along with "*" are significant at 0.05 level.

According to **Table 4**, only positive linear correlations are observed. High significant positive correlations are identified between operating speeds and entry width for each case. Similar correlations are observed between operating speeds and entry radius for each case as well.

The effects of the geometric characteristics of roundabouts on the 85th percentile entry operating speed are presented in **Figure 5** on the scatter diagrams, where a linear relationship has been observed. The relationship between entry width and $V_{1,85}$ and the relationship between entry radius and $V_{1,85}$ confirm the strong correlation.

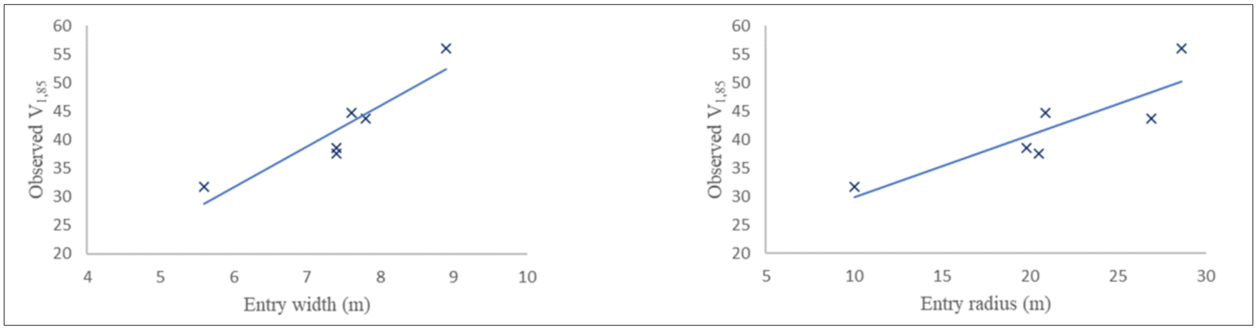

Figure 5 The relationships between observed $V_{1,85}$ and individual geometric design elements of the roundabout

Therefore, the entry, circulating and exit 85th percentile operating speeds are strongly affected by entry width and entry radius of roundabouts. Specifically, speeds become higher as these geometric elements become higher. However, these results are based on limited number of samples and small ranges of geometric features.

The following table presents the comparison of predicted and field-measured speeds for the case study roundabouts, per each examined through movement.

Table 5 Comparison of predicted and field-measured speeds

Roundabout	Through Movement	Calculated design speed (km/h)			V_{85} observed speed (km/h)			Deviation (%)		
		V_1	V_2	V_3	V_1	V_2	V_3	V_1	V_2	V_3
A	1 – 3	50.4	32.8	55.3	43.7	44.2	52.2	-13.3%	34.8%	-5.6%
	4 – 2	48.5	30.6	52.1	44.7	42.6	51.4	-7.8%	39.2%	-1.3%
	2 – 4	48.2	32.9	53.9	38.6	38.8	48.9	-19.9%	17.9%	-9.3%
	3 – 1	47.4	31.6	55.8	37.6	36.0	45.6	-20.7%	13.9%	-18.3%
B	1 – 3	50.3	36.1	68.0	56.0	51.1	52.3	11.3%	41.6%	-23.1%
C	1 – 3	42.5	29.9	48.0	31.7	29.7	35.4	-25.4%	-0.7%	-26.3%

The following figures present graphically the results of this study. Specifically, they present the design speeds that were calculated for the through movements according to the American guidelines (*1*) and OMOE-K3 (*19*) against the actual speeds that were measured through the UAV.

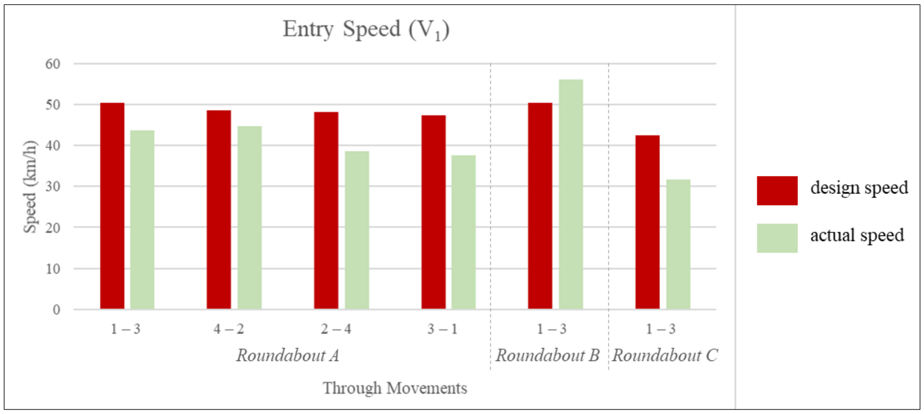

Figure 6 Entry speed

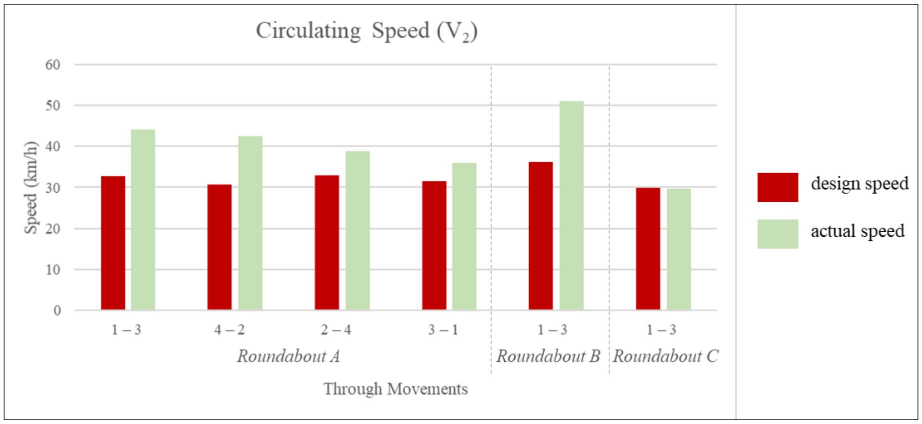

Figure 7 Circulating speed

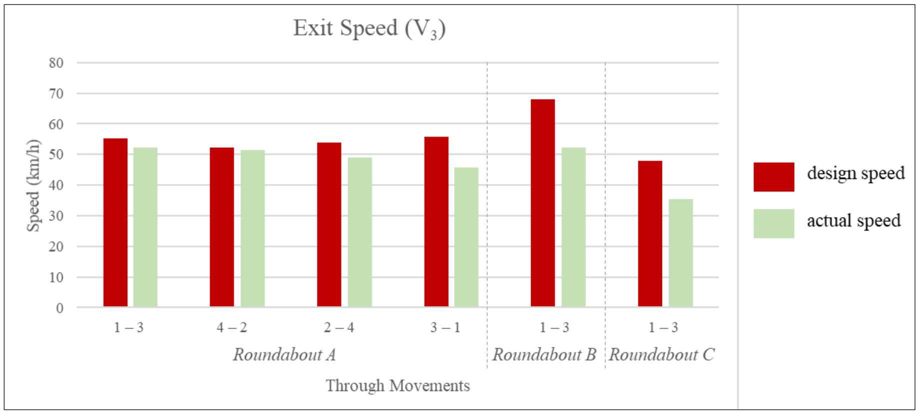

Figure 8 Exit speed

The current method used for predicting V_1, V_2 and V_3 speeds generally overestimates and underestimates 85th percentile speeds in the most cases. This means that the design of the roundabout is not fixated on fastest path as a design tool for the control of entry, circulating and exit speeds.

Specifically, observed entry and exit speeds are significant less than the predicted vehicle speeds according to FHWA methodology, while circulating speeds are higher. According to **Figure 6**, the deviation between design and actual entry speeds ranges between the values of -25.4% and 11.3%. Actual circulating speeds deviate from the design ones from -0.7% to 41.6% (**Figure 7**). Finally, the actual exit speeds are lower than the predicted for each case. Deviations range from -26.3% to -1.3% (**Figure 8**).

Finally, in the case of Roundabout B the actual entry speed is a bit higher than the recommended value according to the guidelines (50 km/h). This can be reasonable because of the large angle between the two legs of the through movement.

The relationship between path radius and speed regarding the estimated and observed through-movement circulating speeds is presented in the following Figure. It is can be concluded that there is an acceptable correlation between the 85th percentile field-measured circulating speed $V_{2,85}$ and the circulating path radius (R_2). It is also confirmed that the FHWA methodology results in conservative values of circulating speeds.

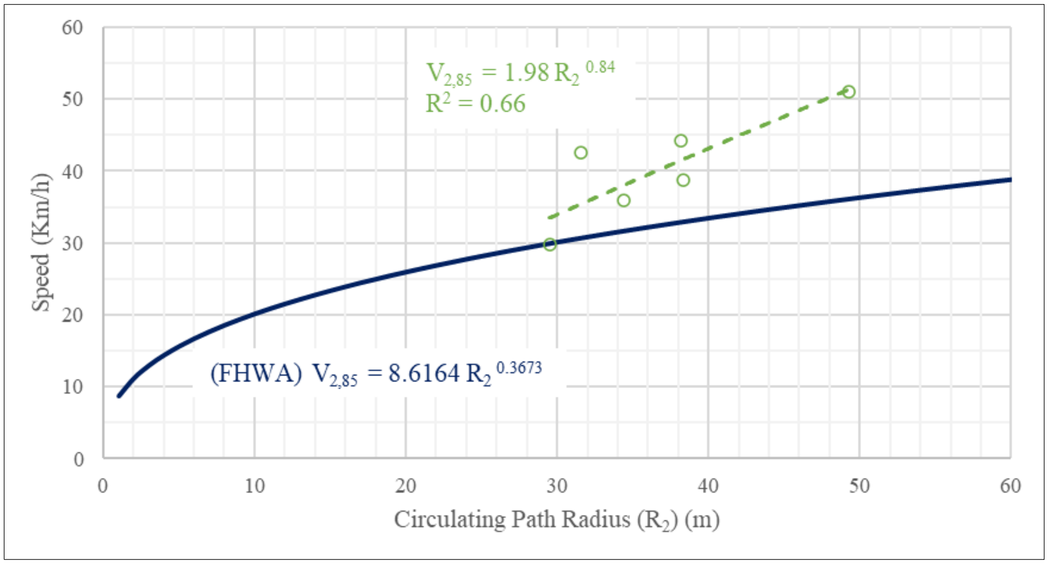

Figure 9 Operating circulating speed as a function of circulating path radius

CONCLUSIONS

This paper presents the results of experimental research that has been conducted as a first step in the development of a vehicle speed model for roundabouts in Greece. The research aims to define the basic path elements of vehicle through movement in a roundabout at which the maximum speed is achieved.

The traffic data acquirement by a UAV is a methodology that researchers and traffic engineers use widely nowadays. The proposed method for extracting detailed naturalistic vehicle trajectories data through UAVs provide a useful tool for obtaining spatiotemporal phenomena at intersections. The accurate calculation of actual speeds is highlighted in this study.

According to the results, it can be highlighted that modern roundabouts that have been constructed recently in Greece, ensure the use of fastest path analysis as a design tool for the control of entry speeds, as the entry design speed is calculated to be close to the recommended maximum value of 50 km/h for all cases. It is noted by the literature that fastest path design control is a major factor for controlling speeds and ensure traffic safety on the road network.

However, the fact that there are significant variations between predicted and observed vehicle speeds means that the reliability of FHWA models is been disputed for implementation regarding the driving behavior of Greek drivers. This method overestimates entry and exit speeds, while underestimates circulating speeds. Specifically, the deviation between design and actual entry speed per each case is between the values of -25.4% and 11.3%. Actual circulating speeds deviate from the design ones ranging from -0.7% to 41.6%, while the actual exit speeds are lower than the predicted. The deviation in this case ranges from -26.3% to -1.3%.

Finally, strong linear correlations between the 85th percentile field-measured entry, circulating and exit speeds and the geometric features of roundabouts (entry width and entry radius) are observed. Moreover, it is highlighted that the FHWA methodology results in conservative values of circulating speeds.

The results are based on limited number of samples and small ranges of geometric features. More case study roundabouts and straight directions through multilane roundabouts should be considered for further analysis and more observed vehicle speeds should be analyzed to develop a reliable vehicle speed model for multilane roundabouts.

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