Transport and Communications Science Journal, Vol. 75, Issue 4 (05/2024), 1544-1554

Transport and Communications Science Journal

A STUDY ON THE CAPACITY ASSESSMENT OF TURBO ROUNDABOUTS AND THE APPLICABILITY IN VIETNAM

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ARTICLE INFO

TYPE: Research Article
Received: 15/04/2024
Revised: 06/05/2024
Accepted: 09/05/2024
Published online: 15/05/2024
https://doi.org/10.47869/tcsj.75.4.6
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Abstract. A turbo roundabout (or Turbine) is an improvement from conventional roundabouts with lanes running in a spiral shape, helping vehicles to enter the intersection smoothly and eliminate conflicts, reducing traffic congestion as well as the risk of traffic accidents. The turbo roundabout is a modern intersection, newly developed around 1996, initially in the Netherlands, then expanded to many European countries, Russia, and North America. In Vietnam, this type of intersection is still a novelty and requires more scientific exploration. Based on research from developed countries and through the use of Vissim traffic simulation software, the paper presents an analysis and evaluation of the effectiveness of Turbo roundabouts compared to conventional roundabouts. The study also proposed and developed shifted exponential models, capable of well describing the nonlinear relationship between capacity of entry roadway with circular flow. Results show that the turbo roundabout is a potential solution for Vietnamese traffic. The study's evaluation using a basic layout of a two-lane turbo roundabout with only automobile traffic composition limits its applicability to mixed traffic environments. Initially, the study proposes the installation of turbo roundabouts on access roads of freeways, or motor highways with low-to-medium traffic volume.

Keywords: Roundabout, turbo roundabout, turbine roundabout, traffic congestion and accident, capacity.

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1. INTRODUCTION

Modern roundabouts have been proven to be a type of intersection with many advantages over traffic circle or rotary intersections in terms of minimizing congestion and traffic accidents. This type of intersection was developed in the 1960s in England, and then applied in many other developed countries around the world including the United States, Germany, France, Russia, Japan, and Australia [1-5]. Over time, modern roundabouts have evolved with a wide range of variations to suit different traffic needs and layouts. Notably, the Turbo roundabout (also known as a Turbine roundabout) is a variation of the modern roundabout developed by Dutch scientist, Lambertus G. H. Fortuijn in 1996 to improve capacity and traffic safety [6, 7]. The Turbo roundabout is shown with traffic lanes in the intersection designed in a spiral shape. This solution helps reduce the number of traffic conflicts, vehicles are "protected" when entering the roundabout, thereby reducing the risk of conflicts, increasing the effectiveness of minimizing traffic congestion and accidents.

Vietnam currently lacks official standards, design guidelines, as well as dedicated research on Turbo roundabouts. This type of intersection has not yet been implemented in practice. While conventional types of traffic circle and rotary intersections exhibit limitations, the risk of congestion and traffic accidents is very high in Vietnam [8]. Meanwhile, turbo roundabouts, a novel intersection design, represent a potential solution for traffic conditions in Vietnam. To ensure the effectiveness and safety of turbo roundabouts in Vietnam, conducting basic research on their suitability for local traffic patterns and road infrastructure is essential.

This paper explores the benefits and functionalities of turbo roundabouts, drawing on existing global research. It then compares them to traditional two-lane roundabouts using traffic simulation software to evaluate their traffic flow capacity. Finally, non-linear regression models are developed to quantify the link between entry capacity and circular flow within the roundabout, leveraging simulation results. Informed by the research outcomes, the paper proposes adaptable solutions for traffic conditions in Vietnam.

2. FEATURES AND ADVANTAGES OF TURBO ROUNDABOUTS

Turbo roundabouts (Fig. 1) have layouts and characteristics different from conventional roundabouts, as detailed below [1]:

- Spiral lanes: Unlike traditional roundabouts, turbo roundabouts incorporate "spiral" lanes on some or all entry points. These lanes curve gradually as they approach the central island, allowing vehicles to enter at a near-perpendicular angle. This design offers several benefits, including smoother entry, enhanced visibility and increased safety. Specially, vehicles are "protected" when entering and merging with traffic on the roundabout (Fig. 1);
- Spiral shape markings direct traffic flows to move smoothly from inside to outside, ensuring smooth flow and eliminating the need for vehicles to cut across each other's paths. Vehicle trajectories are optimized, keeping vehicles in their lane;
- There are more than 2 lanes separated from each other by physical dividers, restricting vehicles from changing lanes within the intersection;
- Designed to accommodate slow speeds due to island shape and diameter, narrower lanes combined with physical guidelines (painted marking, traffic islands);

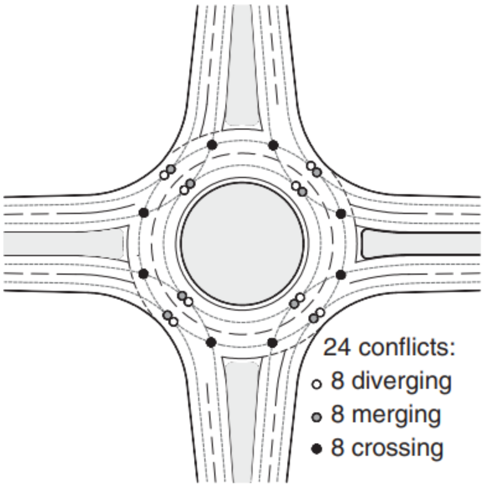
- Turbo roundabout can reduce the impact of uneven vehicle traffic volume at different entrances to the roundabout, as well as save construction costs for multi-lane roundabouts.
- The size of the Turbo roundabout is relatively small;
- Conflict points are reduced as compared to conventional roundabouts (Fig. 2).

a) Plan view b) View from an entry

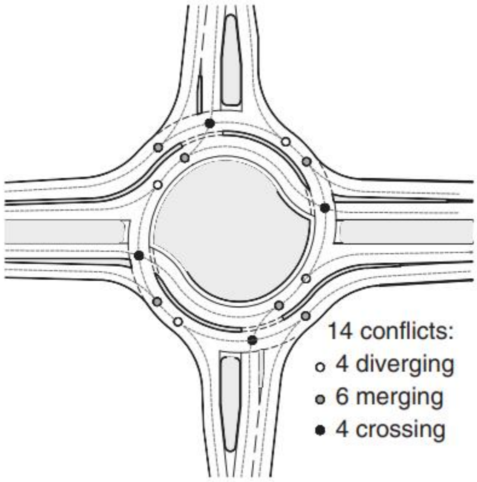
Figure 1. A turbo roundabout in Dutch (Source Google Map).

A substantial body of international research has investigated the performance of turbo roundabouts. From a traffic safety perspective, existing studies show that turbo roundabouts can improve traffic safety compared to many other types of intersections, including signalized intersections and conventional roundabouts. Existing studies in Italy, Netherlands, and Hungary show that turbo roundabouts can reduce collisions, rollover accidents, and accidents involving pedestrians and bicycles [10]; work more effectively than a conventional two-lane roundabout in allowing drivers to navigate correct lane and encouraging safer speed management [11]; have a lower level of casualty risk than a conventional multi-lane roundabout by more than 70% and 80% [7, 12]; 70% safer than regular unsignalized intersections, and 50% at signalized intersections [13].

Research is ongoing to explore how turbo roundabouts affect traffic flow. Early findings suggest potential benefits in reducing wait times and congestion, ultimately improving overall traffic flow [14, 15]. In fact, there are many studies on the capacity efficiency of turbo roundabouts based on comparison with conventional roundabouts. However, the research results are not consistent. This is quite a complex issue depending on the research method, layout of the intersections, traffic flow composition, road user behavior, etc. Some studies suggest that turbo roundabouts have higher capacity than conventional roundabouts [16, 17], while other studies conclude that turbo roundabouts have lower capacity 20%-30%, compared to conventional roundabouts [18, 19]. The generalizability of this approach may be limited. To ensure its efficiency in the Vietnamese context, dedicated research and evaluation are warranted.



a) Conventional roundabout



b) Turbo roundabout

Figure. 2. Comparison of the level of complexity between a Conventional roundabout and a Turbo roundabout [6].

3. EVALUATION OF PERFORMANCE OF TURBO ROUNDABOUT AND APPLICABILITY IN VIETNAMESE CONDITIONS

3.1. Evaluation method and simulation scenario development

This study employs traffic simulation as its primary research method, utilizing the Vissim software developed by PTV Group [9]. Vissim has been widely used to simulate and evaluate traffic network performance. The evaluation of Turbo roundabout intersection is done through comparison with conventional roundabout intersection. The two types of intersections simulated are both basic and common roundabout intersections, which are double-lane roundabout intersections as shown in Fig. 1.

In this study, the criterion of capacity was selected to compare the efficiency of use between two types of intersections. In fact, according to previous studies, the capacity of a roundabout is determined based on the capacity of entry lanes, which itself depends on the circular volume of the roundabout [1-3, 20, 21, 22]. This concept is supported by studies conducted by various researchers and organizations around the world, such as in Russia, Transportation Research Board (TRB), American Association of State Highway and Transportation Officials (AASHTO) in the United States [1-3], as well as similar research in Germany by Brilon, and Road and Transportation Research Association (FGSV) [21, 22].

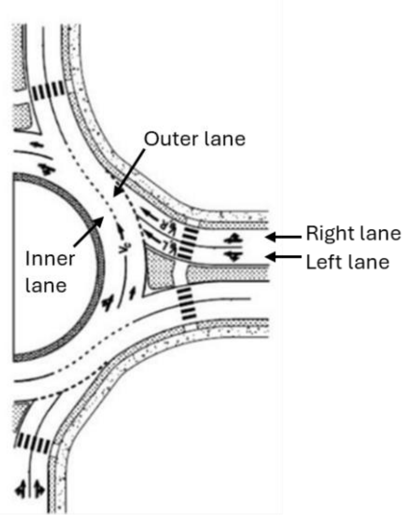
The Highway Capacity Manual (HCM) [20] suggests that a two-lane roundabout's entry lane capacity depends on lane position (left or right) and circulating traffic flow (Eq. (1) and Eq. (2)). However, real-world traffic patterns are more complex. Traffic volume varies within the roundabout, with differences between inner and outer lanes, and across directions at conflict points. These factors can significantly impact the overall capacity of the roundabout's entry lanes, exceeding what the HCM model may fully capture. Generally, the analytical equations HCM [20] have limitations and cannot describe the overall traffic conditions of entry roadways with complex traffic conditions on multi-lane roundabouts.

$$c_{eR} = 1420 * e^{(-0.85*10^{-3})*v_c} \quad (1)$$

$$c_{eL} = 1350 * e^{(-0.92*10^{-3})*v_c} \tag{2}$$

where:

- c_{eR} = Capacity of entry right lane (PCU/h)
- c_{eL} = Capacity of entry left lane (PCU/h)
- v_c = Circular traffic volume (PCU/h)



Note:

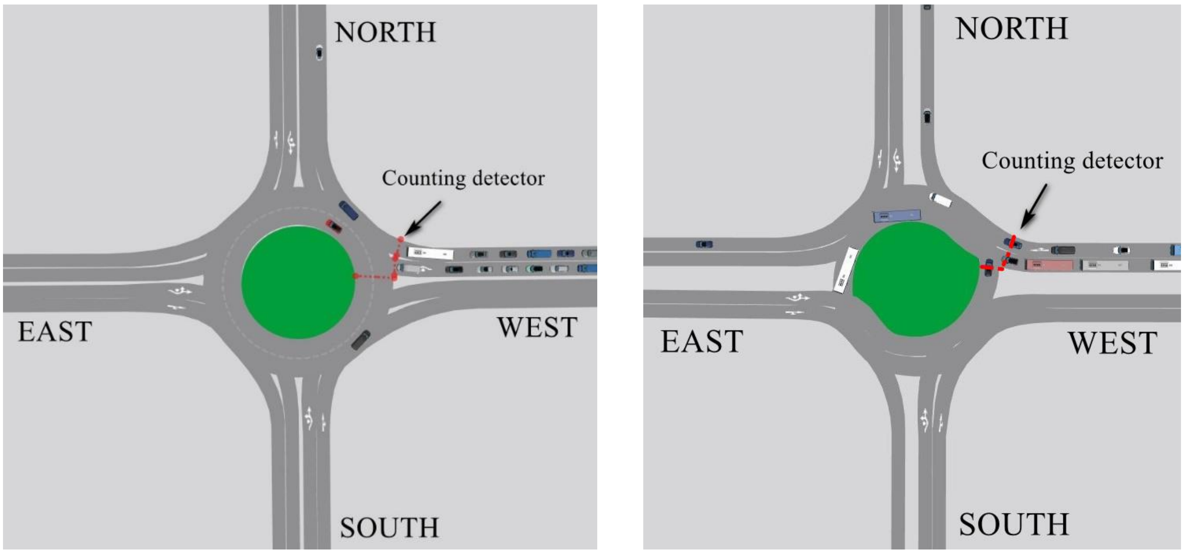
- Inner lane is a lane on the circular roadway closest to the central island.
- Outer lane is the lane on the circular roadway farstest to the central island.
- Right lane is the lane running on the entry roadway on the right side.
- Left lane is the lane running on the entry roadway on the left side.

Figure 3. Illustration of the method for calculating capacity of roundabout intersections according to HCM [20].

This study addresses shortcomings in past research by analyzing the entire road approaching the roundabout, including both lanes, as a single unit. This approach considers how traffic on this approach interacts with the circulating flow within the roundabout to determine capacity more accurately. To specifically evaluate the performance of Turbo roundabouts, traffic simulation scenarios were created. That compared traffic flow at a conventional roundabout to that of a Turbo roundabout. The input data for the specific simulation that include layouts and traffic volume as well as composition are as follows:

- Both intersections are basic roundabouts with 2 lanes (each roundabout has 2 lanes on entry roadways and 2 lanes running around the central island). According to Federal Highway Administration (FHWA), US, the inscribed diameter of the central island of a multilane roundabout ranges from 150 feet (~45 m) to 250 feet (~76 m). In this study, the inscribed diameter for the central island in each intersection is specified to be 45 m.
- One entry roadway was selected for analysis for each simulated scenario, which is from East bound to West bound. Because the layout of lanes for East-to-West traffic differs between the turbo roundabout and the conventional roundabout. In this direction, vehicles entering the turbo roundabout only conflict with 1 lane of the circular roadway, while on the conventional roundabout, conflict with 2 lanes of the circular roadway (Fig. 1 and Fig. 4).

- Input traffic volume in both scenarios includes traffic on the analyzed entry roadway (East to West direction) and circular traffic on the roundabout. Circular traffic volume on the roundabout is imported at the entry roadway from South to North bound direction. Because the conventional roundabout has 2 lanes on circular roadway at the conflict position with the analyzed entry roadway, the input traffic volumes ensures that the traffic flow on the circular roadway of this roundabout can change according to the ratio between the **inner lane** and the **outer lane** (Fig. 3). Traffic flow on circular roadway on the conventional roundabout is changed with 3 levels of ratio between **inner lane/outer lane** (Fig. 3) as **50%/50%**, **25%/75%** and **0%/100%**. Because the turbo roundabout has 1 lane on the circular roadway at the conflict position with the analyzed approached entry roadway, there is only 1 case where 100% traffic volume on the circular roadway at the conflict position. The levels of total traffic entering the circular roadway are changed to levels of 100 veh/h, 150 veh/h, 200 veh/h... until traffic on the circular roadway is saturated. Each case runs Vissim about 16 times. A total of 64 simulations were run across the 4 cases (Refer Table 1 and Figure 5).
- The input traffic composition is only motor vehicles. The composition is referenced according to some previous studies in Vietnam, specifically on some freeways in Hanoi area, the average proportion of passenger cars accounts for about 70%, trucks account for 20% and buses account for 10% [23]. Vehicles entering the intersection from the approach must give priority (yield way) to vehicles from the left (vehicles running on the circular roadway). The speed of vehicles running on the entry roadway is taken to be 60 kph and the speed of vehicles running on the circular roadway is 30 kph [2]. The 60 kph speed of vehicles on entry roadways of roundabouts is also suitable for traffic conditions on typical access roads of freeways in Vietnam.



a) Simulation of the conventional roundabout　　b) Simulation of the turbo roundabout

Figure 4. Simulation scenarios for the comparison (Captured from Vissim interface).

- In each scenario (at each roundabout), vehicle counting sensors were placed at each lane on the circular roadway and each lane on the entry roadway at the conflict position between them. The volume of vehicles counted is then converted into equivalent passenger car unit (PCU/h). The output data is the traffic flow on the circular roadway and the number of vehicles that can enter the roundabout from the entry roadway (at the conflict location as shown in Fig. 4).

3.2. Simulation results and modeling of the capacity curves

The simulation results are shown in Tab.1 and Fig. 5. The results show that the capacity of the entry roadway reaches an average of about 3000 PCU/h under zero traffic volume conditions on the circular roadway. When the traffic volume on the circular roadway increases, the capacity of the entry roadway will decrease. For the conventional roundabout, when changing the traffic ratio between the **inner lane/outer lane** of circular roadway, the traffic flow of the entry roadway also changes. Specifically, when the ratio is **50%/50%,** the capacity of analyzed entry roadway is the highest in the 3 cases, and the smallest when the ratio is **0% /100%**. In the case of a traffic ratio of **0%/100%**, when the circular traffic volume reaches about 1600 PCU/h, the entry capacity is close to zero. However, for the case of **50% /50%,** the entry capacity reaches 0 PCU/h only when the total circular traffic volume reaches about 3000 PCU/h. The results also show that at the ratio of **0%/100%**, the entry capacity at the conventional roundabout is approximately the same as at the Turbo roundabout. This result is also completely reasonable, because at the location of the conflict between the circular roadway and analyzed entry roadway, there is only 1 lane at the Turbo intersection. In particular, the results show that with medium and low circular traffic volume, the difference between capacity of entry roadway at turbo roundabouts and conventional roundabouts is not so significant (Fig. 5).

The results also show that, in all 4 simulation cases with two scenarios: conventional roundabout and Turbo roundabout, the data tends to follow an exponential function. This is also consistent with many previous theoretical and experimental studies. The results are also consistent with Eq. (1) and (2) presented in HCM [20].

However, from HCM's equations [20], it shows that when circular traffic volume increases to saturation level, the capacity of the entry lane does not decrease asymptotically to zero level of congestion. This does not reflect the actual traffic flow. On that basis, this study proposes a mathematical model to describe the capacity curve of roundabouts following the Shifted exponential model according to Eq. (3):

$$C_e = X_1 * e^{(X_2)*v_c} - X_3 \quad (3)$$

Where:

- C_e= Capacity of entry roadway (PCU/h)
- v_c = Circular traffic volume (PCU/h)
- X_1, X_2, X_3 are constants, where X_3 is representative for the displacement of C_e to 0.
- The improvement of this equation is to propose the coefficient X_3 to represent the displacement of C_e to the value 0.

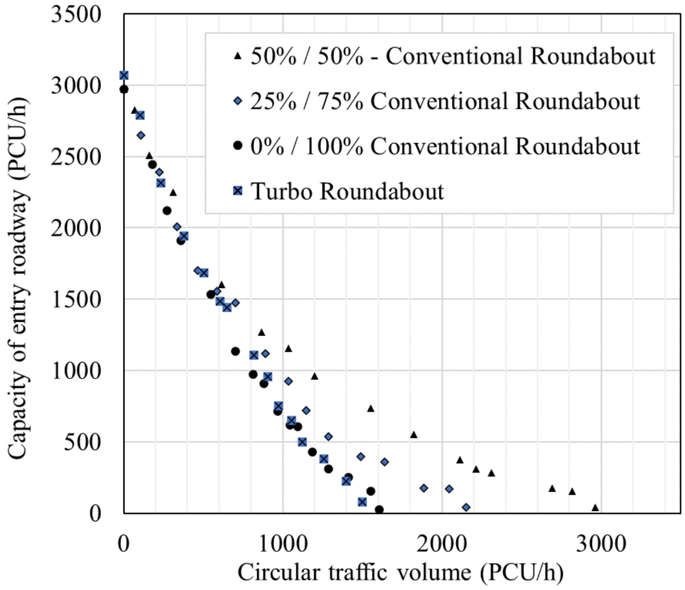


Figure 5. Correlation between circular traffic volume and capacity of entry roadway.

Table 1. Summary of simulation outputs.

No	Conventional roundabout						Turbo roundabout	
	50%/50%		25%/75%		0%/100%			
	Circular traffic volume	Entry capacity	Circular traffic volume	Entry capacity	Circular traffic volume	Entry capacity	Circular traffic volume	Entry capacity
	PCU/h	PCU/h	PCU/h	PCU/h	PCU/h	PCU/h	PCU/h	PCU/h
1	0	2973	0	2973	0	2973	0	3070
2	70	2827	109	2649	179	2446	105	2786
3	164	2511	226	2390	273	2122	235	2317
4	312	2252	335	2009	359	1912	381	1944
5	616	1604	468	1701	546	1531	502	1685
6	866	1272	585	1555	702	1134	608	1482
7	1037	1158	702	1474	811	972	648	1442
8	1201	964	889	1118	881	907	818	1110
9	1552	737	1037	923	967	713	907	956
10	1825	551	1147	721	1045	616	972	753
11	2114	373	1287	535	1092	608	1053	648
12	2215	308	1490	397	1186	429	1123	499
13	2309	284	1638	356	1287	308	1256	382
14	2691	178	1888	178	1412	251	1396	226
15	2816	154	2044	170	1552	154	1498	78
16	2964	41	2153	40	1607	24	1615	31

Table 2. Summary results of forecast models.

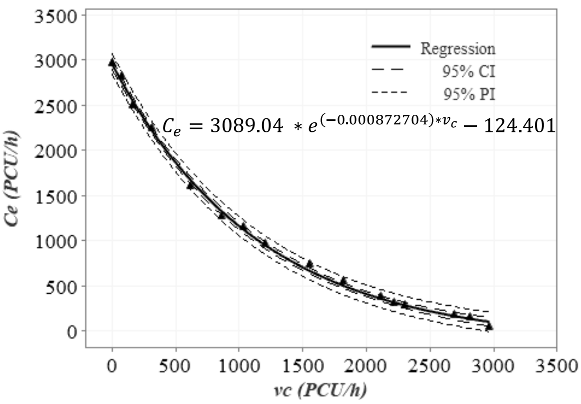
Stt	**Scenarios**		**Formulas proposed by the authors**		**Evaluation indexes**	
					R²	***S***
1	**Turbo roundabout**		$C_e = 4410.9 * e^{(-0.000747866)*v_c} - 1334.51$	(4)	0.998	44.44
2	**Conventional Roundabout**	50%/50%	$C_e = 3089.04 * e^{(-0.000872704)*v_c} - 124.401$	(5)	0.996	59.86
3		25%/75%	$C_e = 3365.57 * e^{(-0.000936905)*v_c} - 389.236$	(6)	0.998	36.39
4		0%/100%	$C_e = 3775.76 * e^{(-0.000937304)*v_c} - 782.65$	(7)	0.997	44.63

- C_e is the capacity of the entry roadway (2 lanes) of the roundabout (PCU/h)

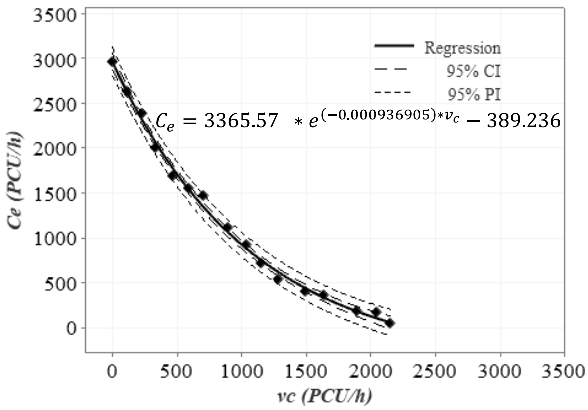
- v_c is the circular traffic volume (PCU/h).

- Eq. (4) presents the capacity of the entry roadway of the Turbo roundabout. Eq. (5), (6), and (7) present the capacity of entry roadway of the conventional roundabout corresponding to the traffic ratio between the **inner lane/outer lane** of **50% / 50%, 25%/75%** and **0%/100%**.

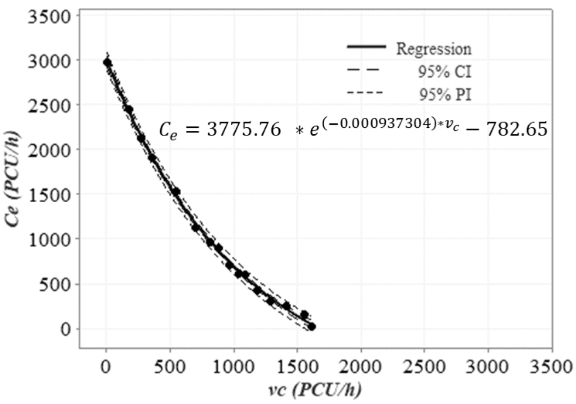
To estimate the parameters X_1, X_2, X_3, nonlinear regression method is used. In this study, the results are expressed through Eq. (4), (5), (6) and (7) and presented in Tab. 2 and Fig. 6.



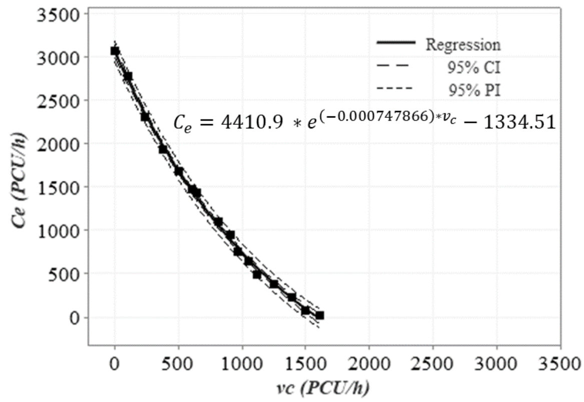
a) Conventional roundabout (50%/50%)



b) Conventional roundabout (25%/75%)



c) Conventional roundabout (0%/100%)



d) Turbo roundabout

Figure 6. Nonlinear regression models with 95% CI and 95% PI ranges.

To evaluate the quality of the proposed forecast models, the indicators R^2 and *S* index, as well as the envelope 95% CI (95% confidence interval) and 95% PI (95% prediction interval) were used as shown in Tab. 2 and Fig. 2. The results show that R^2 is very close to 1, showing that the developed models have a very high fit to the data set. However, R^2 is often better suited to a linear model, so the *S* index as well as the 95% CI (95% confidence interval) and 95% PI (95% prediction interval) were used in addition for non-linear model evaluation. S represents the standard deviation of the distance between the data values and the fitted values. The results show that the proposed models are reliable.

4. CONCLUSION

Existing conventional roundabouts have several disadvantages. Along with the continuous growth of means of transport as well as the complexity of traffic flow as well as road user behavior, new solutions are needed to control traffic at existing intersections of the road network. Turbo roundabouts offer a promising solution, potentially outperforming conventional designs.

Vissim traffic simulation model was adopted to build scenarios to compare the effectiveness of the turbo roundabout with a conventional roundabout (each roundabout also has 2 entry lanes and 2 circular lanes). The results show that the Turbo roundabout has a lower capacity than the conventional two-lane roundabout. However, it is no less effective in terms of traffic efficiency than a conventional roundabout at low and medium traffic volume conditions. At the same time, the traffic safety effects are higher, and the road surface area occupied is less. Therefore, it is recommended that this type of intersection can be initially applied in areas with low-to-medium traffic volumes. This could be particularly suitable for access roads of freeways in Vietnam where traffic consists solely of automobile vehicles. Additionally, it could be a viable option for improving safety in high-density traffic areas, once its effectiveness is proven.

This study demonstrates that the entry capacity of roundabout intersections follows an shifted exponential function, providing valuable prediction models for designing two-lane roundabouts, especially two-lane turbo roundabouts, in situations where simulation tools are unavailable.

The current study focused on a limited scope, comparing only two-lane conventional roundabouts and basic turbo roundabouts with a typical automobile traffic composition. Given the existence of diverse turbo roundabout design configurations, further research is warranted to explore the performance of these variations and identify optimal designs for Vietnamese traffic scenarios.

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