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Article

Using a Microsimulation Traffic Model and the Vehicle-Specific Power Method to Assess Turbo-Roundabouts as Environmentally Sustainable Road Design Solutions

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Abstract: The European Union's path towards zero carbon dioxide emissions for new passenger vehicles necessitates a transitional period in which conventional vehicles coexist with zero-emission alternatives. This shift requires targeted strategies from engineers and policymakers, particularly in the area of road design, to reduce pollution. This study aims to investigate the environmental benefits of converting a two-lane urban roundabout into a turbo-roundabout through a virtual microsimulation approach using PTV VISSIM. The simulated model was calibrated and validated with real-world daily traffic data by properly adjusting the driving behavior parameters and comparing observed and modeled traffic volumes and queues. The Vehicle-Specific Power (VSP) emission method was applied to model, calculate and illustrate emissions by analyzing vehicle trajectories for the examined scenarios. Results show a statistically significant reduction in emissions for nearly all trips, with emissions decreasing by up to 44% across the intersection and its surrounding areas, and up to 23% at the intersection itself. Emissions are largely influenced by trip duration and traffic efficiency, both of which are enhanced by the improved geometric configuration of the case study intersection. These findings highlight that turbo-roundabouts represent an effective, environmentally sustainable design solution for urban intersections.

Keywords: turbo-roundabout; pollutant emissions; VSP; VISSIM; microsimulation; road geometry

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1. Introduction

The European Union (EU) has set a new path towards zero carbon dioxide (CO_2) emissions. As stated in [1], the European Commission (EC) has recently implemented an initiative for greenhouse gas (GHG) emissions. More specifically, the EU has committed to reducing its GHG emissions by at least 55% by 2030 relative to 1990 levels [2]. Among the key elements of the "Fit for 55" package, transport sector transformation is among the most critical. Since road transport is responsible for 73.2% of total European transport emissions [3], the EU has set the path towards zero CO_2 emissions by strengthening the carbon dioxide emission performance standards for new passenger cars and new light commercial vehicles in line with the Union's increased climate ambitions [1].

In recent years, environmental and transportation researchers have followed various approaches and strategies aimed at addressing the growing challenges of sustainable urban mobility. A key objective continues to be the transitioning to low-emission transportation systems such as electric vehicles and active transportation to minimize environmental impacts [4,5]. However, the increasing levels of traffic congestion, concurrent with the coexistence of both conventional and zero-emission vehicles, particularly in urban areas, emphasizes the importance of adopting a more comprehensive, multimodal approach to transportation [6]. This approach involves not only promoting cleaner modes of transport, but also fostering better integration between them and implementing different schemes of urban vehicle access regulations schemes, such as low emission zones (LEZs) and zero emission zones (ZEZs) [7,8].

A number of relevant studies [9] have increasingly focused on the reassessment of road system design in order to mitigate air pollution. However, any intervention in road design should be carefully implemented to prevent the "rebound effect". For instance, if a road design change makes driving more efficient, it could lead to increased traffic flows and potentially negate pollution reduction efforts [10]. According to [11], increasing road infrastructure capacity will improve air quality, only if it is integrated into a broader urban transport strategy that includes measures to limit vehicle use and promote local environmental protection. Furthermore, the design of the new infrastructure should aim to minimize the potential for creating hot spots (such as CO and PM concentrations).

In that context, roundabouts are an attractive alternative for at-grade intersections, as they notably enhance both road safety and capacity [12–15]. In addition to improving traffic flow, roundabouts can also contribute to reducing vehicle emissions and fuel consumption by minimizing delays and queues [16,17]. Moreover, before-and-after studies [18–21] on converting signalized intersections into roundabouts have shown significant reductions in pollutant emissions. However, the design of roundabouts requires changes to vehicle speed, particularly in free-flow conditions. This can result in higher acceleration and deceleration rates, potentially leading to increased pollutant emissions [21,22].

Turbo-roundabouts are among the most recent geometric variations of roundabouts and are primarily a European innovation, as their acceptance and popularity has been demonstrated in many EU countries [23,24]. To be more specific, a turbo-roundabout is an advanced type of traditional two-lane roundabout designed to improve traffic flow and safety. In a turbo-roundabout, drivers select their entry lane in advance, based on their intended exit, and must remain in that lane while navigating the intersection. This design minimizes lane-changing and reduces accident risk, enhancing the efficiency of maneuvering through the roundabout [25].

Recent studies also suggested that turbo-roundabouts show intermediate performance levels compared to various types of conventional roundabouts (single-lane and multi-lane) [26,27]. To the best of the authors' knowledge, while the operational and safety performance of turbo-roundabouts has received substantial interest, there has been less prior research on the effects on pollutant emissions.

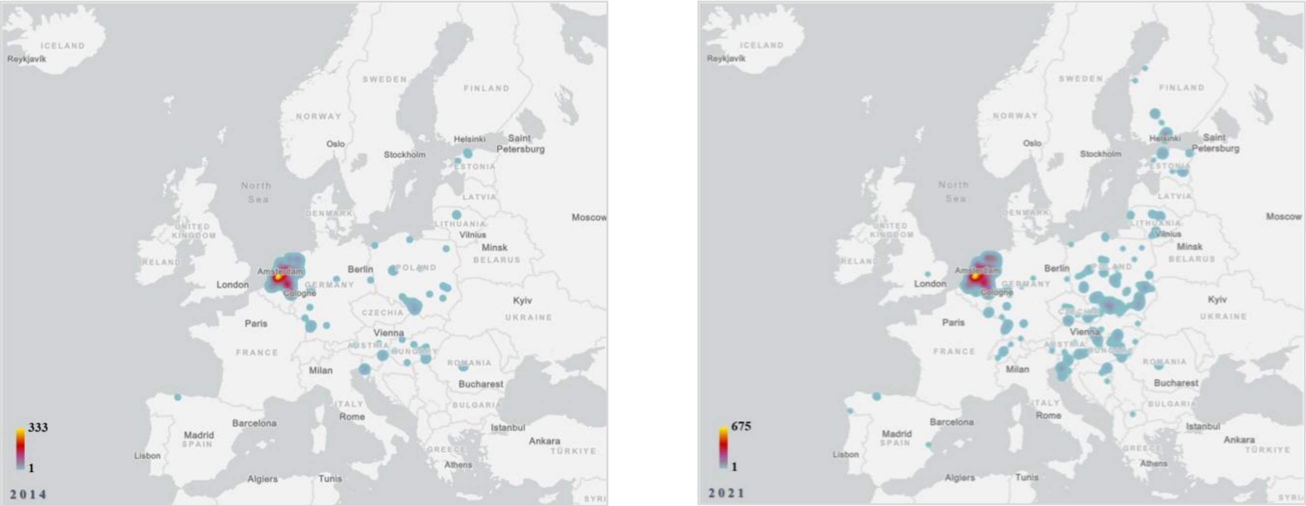
Hence, the main objective of this paper is to contribute to current knowledge by investigating and comparing the environmental performance of a virtual turbo-roundabout as an alternative to an existing multilane roundabout. More specifically, this study aims to analyze and assess the expected benefits, using a microsimulation approach though PTV VISSIM, based on existing traffic conditions in the city of Larissa, Greece. The microsimulation model was calibrated and validated according to on-field traffic data collected over a one-week period during peak hours to ensure a representative dataset for analysis. Vehicle trajectories were extracted, and the Vehicle-Specific Power (VSP) emission method was applied to calculate the major pollutant, CO_2. The objectives of this study also include analyzing differences in vehicle emissions, travel speed, and acceleration between existing multilane roundabouts and the virtual turbo-roundabout. The identification of hotspot emission locations is crucial in initiating a discourse on the environmental performance of this configuration.

The remainder of this study is organized as follows. The background section provides a comprehensive review of relevant existing literature and research. Subsequently, the employed methodological framework for collecting and simulating naturalistic driving behavior data is presented, followed by a comprehensive description of the vehicle emissions calculation using the Vehicle Specific Power (VSP) method. The results of the statistical analysis regarding the comparison of the multilane roundabouts, and the virtual turbo-roundabout are then presented and discussed. Finally, the last section summarizes the key findings of the study.

2. Background

2.1. Turbo-Roundabouts as an Alternative to Multilane Roundabouts

Turbo-roundabouts are among the most prominent roundabout design practices, and have been increasingly adopted, particularly in Europe and also in other regions around the world. Figure 1 illustrates the rise in the construction of turbo-roundabouts in Europe from 2014 to 2021 [28] based on the dataset from Dirk de Baan [29]. This roundabout configuration is primarily located in Europe, especially in countries like the Netherlands, Germany, Poland, the Czech Republic, Hungary, and Belgium.



(**a**) (**b**)

Figure 1. The increase in the construction of turbo-roundabouts in Europe from 2014 (**a**) to 2021 (**b**) [28].

This form of roundabout was first introduced in the Netherlands in 2000. In 1996, Lambertus Fortuijn [25] conceptualized the concept of the turbo-roundabout, aimed at increasing traffic capacity, reducing vehicle speeds, and ensuring the selection of a predetermined lane, both within the roundabout and at its approaches without the need for lane changes. Consequently, this design reduces the frequency of lateral conflicts and accidents, and, thus, significantly enhances the overall level of road safety. The main characteristics of a turbo-roundabout are summarized as follows, as stated in [25]:

- Introduction of an additional traffic lane on the roundabout's circulating carriageway, and at least at one entry lane.
- Priority is granted to no more than two circulating lanes on the roundabout.

- The use of a spiral layout promotes smooth traffic flow.
- Use of raised lane dividers for traffic separation.
- Lane choice and direction are determined at the entrance and cannot be changed within the roundabout.
- At least two exits consist of two lanes.
- Optimal curvature for vehicle trajectories is achieved by using a small diameter for the roundabout.
- A traversable apron on the central island is used to accommodate heavy vehicles.

It is worth noting that, mostly in Germany [30], as well as in other countries [31], the use of raised geometrical elements for lane separation is discouraged. Instead, lane markings are recommended for two main reasons:

- Increased motorcyclist safety.
- Simplified road maintenance, particularly during winter.

The benefits of turbo-roundabouts have been widely investigated in the international literature, and they are a preferred form of roundabout, whether when replacing signalized at-grade intersections or retrofitting existing roundabouts [32,33]. Existing research on converting existing roundabouts into turbo-roundabouts has focused primarily on improving road safety [25,34–36]. As for traffic capacity, while significant benefits have been observed [37,38], it is suggested that the distribution of traffic volume at roundabout approaches may negatively impact capacity [39–41].

Regarding pollutant emissions, results are mixed, depending largely on the type of existing roundabouts and the traffic distribution [42–45]. For instance, a recent study [46] demonstrated that turbo-roundabouts have the potential to be environmentally sustainable when traffic parameters are managed to ensure continues and congestion-free flow. On the other hand, stop-and-go conditions can lead to harmful gas emissions and high levels of fuel consumption.

Actions aimed at improving transport demand (modal shift) and supply (road infrastructure) to mitigate air pollution are discussed in [47]. To further investigate the approach of improving transport supply, the authors assessed the conversion of a multilane roundabout to a turbo-roundabout in order to evaluate its potential for reducing environmental impacts. Moreover, a micro-simulation analysis was applied in VISSIM [48], and pollutants were estimated by using the VERSIT+ emission-calculation software [49]. The results showed that the geometric and functional redesign of the roundabout can reduce vehicle emissions by up to 30%, considering the current traffic composition and existing vehicle technology. Overall, this study highlights the significant environmental benefits that can be achieved through the thoughtful redesigning of roundabouts.

2.2. Road Design and Sustainable Mobility

The factors influencing fuel consumption and road transport emissions can be categorized into five main groups, according to [50]:

- driving behavior,
- vehicle fleets and characteristics,
- traffic conditions,
- road geometry, and
- environmental factors.

Driving behavior, traffic conditions, and road geometry play a significant role in vehicle maneuvers and speed fluctuations, which directly affect pollutant emissions. Meanwhile, the vehicle fleet, vehicle-specific characteristics, and environmental conditions (e.g., temperature, humidity, atmospheric pressure) have a direct impact on fuel consumption and emissions.

These issues have been widely acknowledged through the analysis of vehicle trajectories and speed profiles [16,51–54]. Vehicle trajectories provide valuable insights into vehicle kinematic characteristics (e.g., speed, acceleration, deceleration), driving behavior (e.g., gap acceptance), and traffic conditions (e.g., traffic congestion). Various methodologies and simulation tools have been used to compare pollutant emissions between roundabouts and signal-controlled intersections [55]. The findings indicate that in the absence of traffic congestion, roundabouts may result in higher pollutant emissions, largely due to driving behavior as a key contributing factor.

Furthermore, similar studies from the US [56] have revealed that the environmental benefits of converting signalized intersections into multilane roundabouts depend largely on traffic distribution. In this context, variations in driving behavior significantly affect the total volume of pollutant emissions [57,58]. Although roundabouts are typically associated with smoother traffic flow, shorter queues, and fewer delays and stops, under free-flow conditions they can still result in increased air pollutant emissions due to driving behavior and significant speed variations.

3. Methodology

The research framework implemented is divided into three distinct sections, as presented in Figure 2.

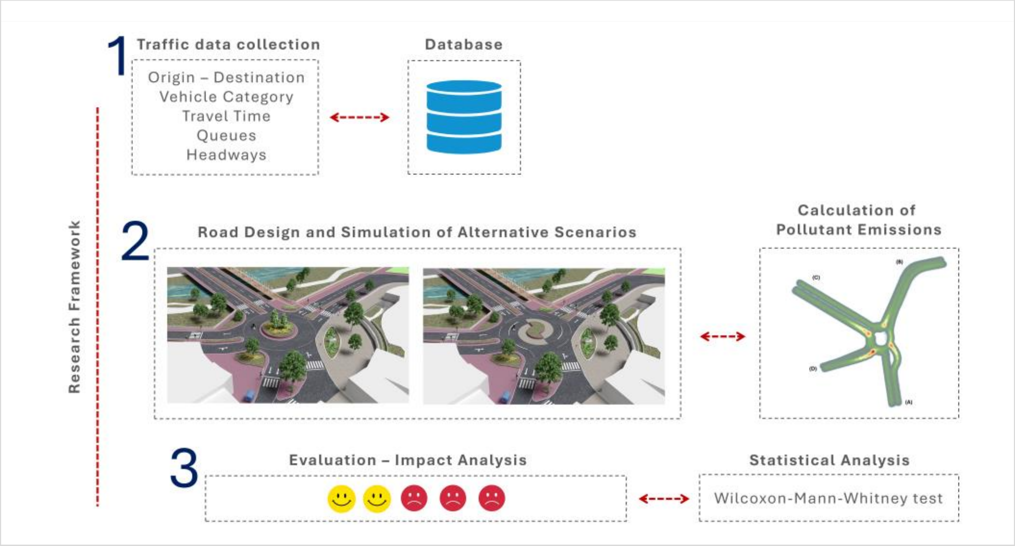
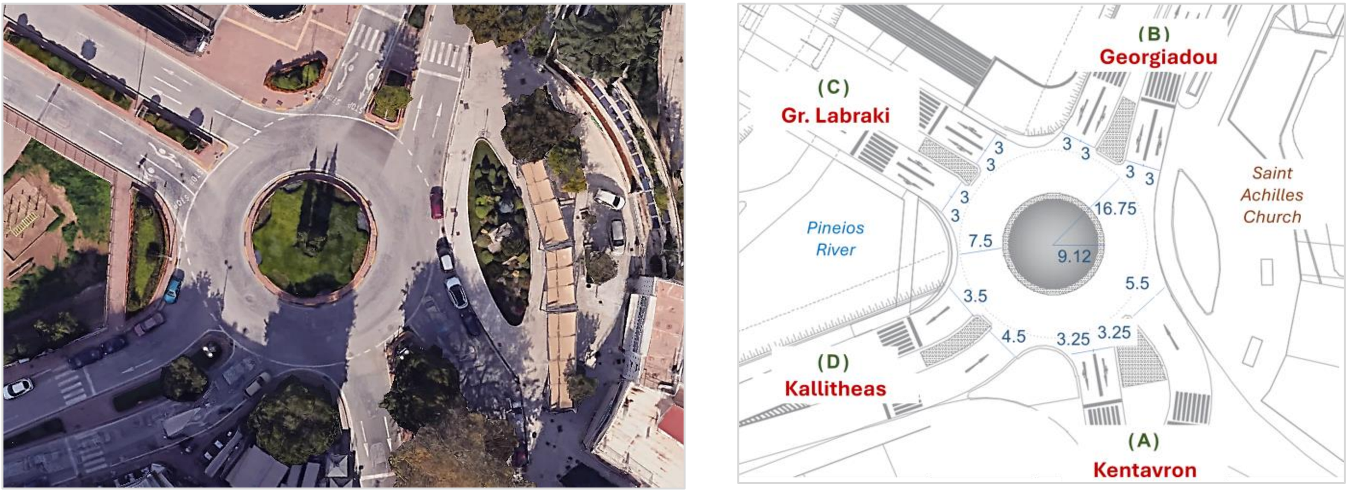


Figure 2. Research framework.

First, traffic data were collected over a one-week period during peak hours to ensure a representative dataset for analysis, in the city of Larissa, Greece (please see Section 3.1 below for more details). The microscopic traffic simulation model, PTV VISSIM, was employed to simulate traffic conditions under various alternative scenarios, including the proposed turbo-roundabout configuration. Calibration and validation of the model were performed in accordance with established criteria to ensure accuracy and reliability. More specifically, both the parameters of the Wiedemann 74 car-following model and conflict area parameters were adjusted to accurately simulate real-world driving behavior (see Section 3.2.1). Following the simulation, pollutant emissions were calculated using the Vehicle-Specific Power (VSP) methodology, allowing for a comprehensive assessment and comparison between the existing and proposed configurations. Statistical analysis, alongside spatial analysis of the modeled carbon dioxide emissions, underscored the environmental benefits of the turbo-roundabout design. The findings highlight the potential of this geometric reconfiguration to significantly reduce emissions, demonstrating its viability as a sustainable solution for improving air quality in urban traffic environments.

3.1. Traffic Surveys and Data Collection

A multilane roundabout located in the urban area of Larissa, Greece, was selected for this study, as illustrated in Figure 3a. This roundabout mostly serves left-turning movements and right-turning movements. It provides connections to the central business district (CBD) of the city from north and east directions. Regarding speed control, major and minor roads have a 40 kph speed limit. The main geometric characteristics, as given by the Municipality of Larissa, are depicted in Figure 3b.



(**a**) (**b**)

Figure 3. Analyzed multilane roundabout located in Larissa, Greece. (**a**) Aerial view of the selected roundabout. (**b**) Geometric characteristics of the selected roundabout.

To ensure the accurate collection of traffic data under saturated conditions, initial field observations were scheduled during three distinct time periods: morning peak (08:00–09:00), afternoon (13:00–14:00), and evening (20:00–21:00) on a typical weekday. These time slots were determined based on a preliminary analysis of traffic delays derived from Google Maps API over the course of a tested month. Based on the preliminary results, the morning peak hour (08:00–09:00) was identified as the period with the highest traffic saturation and was consequently selected for conducting the traffic surveys.

Field data were collected during the morning peak hour over a week with dry weather conditions. A video camera was installed atop the nearest building to capture the full range of movements inside the intersection. This approach ensured that no personal data were collected, maintaining compliance with data privacy standards. Video processing techniques were manually applied by collecting timestamps of specific events using video editing software [59]. It is noted that pedestrian movements and traffic signalizations were not considered in the present analysis as they were out of the scope of the paper.

The following data were collected from the aforementioned field surveys:

- Traffic volumes (in PCU/h);
- Vehicle type (car, motorcycle, bus, light goods vehicle, heavy goods vehicle);
- Origin–Destination (OD) matrices;
- Travel time (in min);
- Queues (in meters);

- Follow-up headways (t_f), calculated using the move-up method (in sec); and
- Critical headways (t_c), calculated using the maximum likelihood method by performing a logistic regression on the accepted and rejected gaps (in sec).

Table 1 shows the OD matrix for the morning peak hour as resulted from the traffic surveys. It is noted that traffic counts were converted into passenger car units (PCUs).

Table 1. The O-D matrix of the morning peak hour for the current situation.

O/D (Roundabout Approach)	A	B	C	D
A	0	146	317	24
B_{right}	5	0	315	11
B_{left}	243	0	8	199
C_{right}	314	121	0	48
C_{left}	161	299	0	3
D	84	167	84	0

3.2. Traffic Simulation of Alternative Intersection Types

3.2.1. Base Scenario

The microscopic traffic simulation model PTV VISSIM [47] was employed to simulate traffic conditions for alternative scenarios for different intersection types (existing vs. turbo). Each simulation ran for a total duration of 4800 s, including a 1200 s warm-up period, to account for the initial under-saturation of the model. The base scenario model (existing situation) was simulated, calibrated and validated according to existing field observations.

Calibration of the model was conducted by iteratively adjusting key driving behavior parameters to align the model outputs with observed data. Validation was subsequently performed by comparing the simulated results against an independent dataset, ensuring that key performance indicators such as traffic volumes and maximum queue lengths were within acceptable error margins.

More specifically, during the calibration process, both the parameters of the Wiedemann 74 car-following model and conflict area parameters were adjusted to accurately simulate real-world driving behavior, using field-measured follow-up and critical headways for each roundabout approach. Iterative adjustments to the conflict area parameters minimized discrepancies between observed and simulated headways.

Table 2, which follows below, presents the default and the calibrated values for the parameters used for the simulation of the model.

Table 2. The default and the calibrated values for the parameters used for the simulation of the model.

Parameter	Values
Default values of Wiedemann 74 in VISSIM	ax: 2.0 m, bx_{add}: 2.0 m, bx_{mult}: 3.0 m
Calibrated values of Wiedemann 74 in VISSIM	ax: 1.5 m, bx_{add}: 1.2 m, bx_{mult}: 1.5 m
Default values of the conflict area attribute meso critical gap in VISSIM	3.5
Calibrated values of the conflict area attribute meso critical gap in VISSIM	3.5 to 4.7

The calibration criteria followed guidelines provided by the FHWA [59], ensuring that at least 85 percent of the links closely match field conditions. Specifically, for individual links, over 85% of the differences between actual and simulated counts should fall within 100 vehicles per hour for volumes below 700 vehicles per hour. Additionally, the total error in simulated link counts should be within 5% of the total actual counts.

Finally, the GEH Statistic was calculated, and was used to compare the field counts and the model-estimated volume. According to [60], the GEH Statistic for individual link flows should be less than 5 for more than 85 percent of cases. The GEH Statistic formula is defined by Equation (1) [61].

$$\mathrm{GEH} = \sqrt{\frac{(\mathrm{E}-\mathrm{V})^2}{(\mathrm{E}+\mathrm{V})/2}} \tag{1}$$

where

E: model estimated volume in veh/hour

V: field count in veh/hour

Our simulations showed that all calibration criteria were met. More specifically, the calibration process achieved GEH Statistic of less than 4 for all traffic volumes at the roundabout approaches, with the highest observed value being 1.33. Moreover, the maximum queue length errors between the VISSIM simulation and on-field survey were found to be within acceptable limits, with a maximum discrepancy of 7.6% (approach D). Both metrics demonstrate the model's capability to accurately replicate real-world traffic conditions and its robustness in evaluating and testing alternative scenarios.

Figure 4 shows the GEH Statistic for each approach, while Figure 5 compares the observed and modeled maximum queue lengths per approach for the calibrated model.

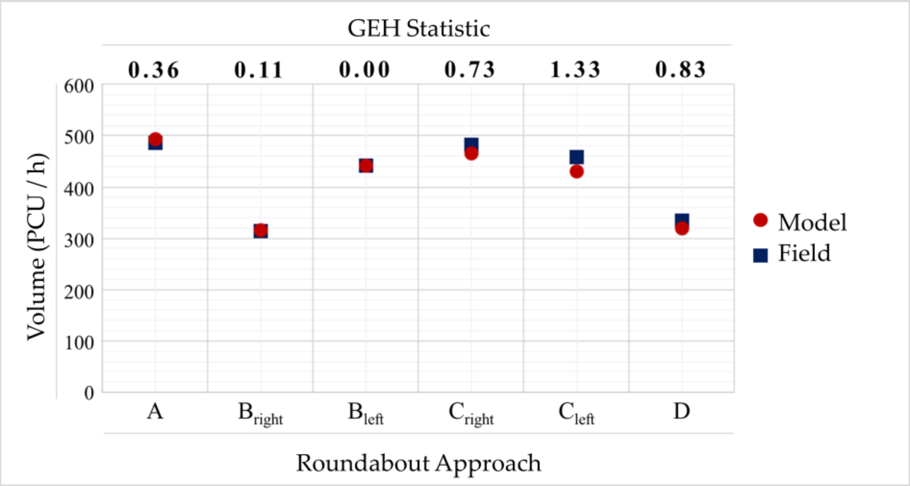


Figure 4. GEH Statistic results for each approach.

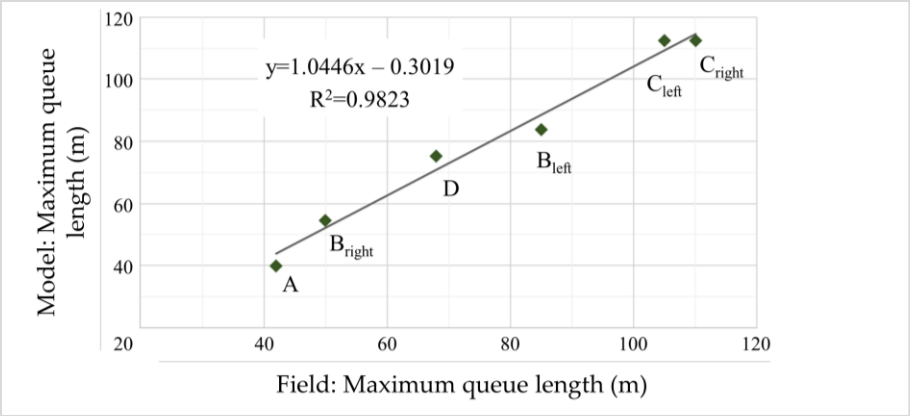


Figure 5. Comparison of the observed and modeled maximum queue lengths per roundabout approach.

3.2.2. Turbo-Roundabout Scenario

Following the calibration and validation of the base scenario to capture and model existing traffic conditions, a virtual turbo-roundabout will be tested and analyzed as a potential alternative to the current multilane roundabout. To rigorously assess the impact of the turbo-roundabout configuration, key geometric features, such as radii dimensions and circulatory lane width, were carefully selected to ensure that vehicle speeds within the intersection do not exceed 40 km/h. Figure 6 shows the geometric aspects of the case study roundabout after its virtual conversion into a turbo-roundabout as was analyzed in PTV VISSIM.

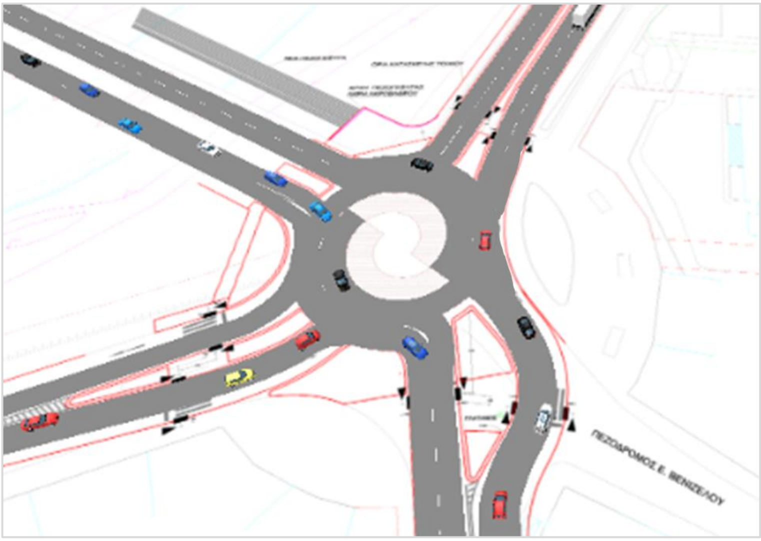


Figure 6. Turbo-roundabout scenario as implemented for analysis in PTV VISSIM.

Figure 7 depicts the existing layout (a) and (b) post-implementation layout of the roundabout at the case study intersection, as rendered by Anagnostopoulos in [28].


(**a**) (**b**)

Figure 7. Before-and-after layouts of the examined roundabout. (**a**) Existing situation. (**b**) Virtual conversion into a turbo-roundabout [28].

3.3. Calculation of Emissions

To calculate vehicles' emissions, vehicle trajectories for both scenarios were exported from VISSIM and further elaborated. The Vehicle-Specific Power (VSP) emission model [62] was applied to calculate the major pollutant, carbon dioxide (CO_2).

The VSP model is presented in Equation (2).

$$\mathrm{VSP} = \frac{\frac{d}{dt} \times (K_e + P_e) + F_r \times v + F_a \times v}{m} \quad (2)$$

where

K_e: kinetic energy (joules),
P_e: potential energy (joules),
F_r: rolling resistance force (newtons),
F_a: aerodynamic drag force (newtons),
m: mass (kg), and
v: vehicle velocity (m/s).

The simplified and applicable form of this model is presented in Equation (3).

$$\mathrm{VSP} = v[1.1a + 9.81(\sin(\arctan(\mathrm{grade})) + 0.132] + 0.000302v^3. \quad (3)$$

where

v: speed (m/s),
a: acceleration (m/s^2), and
grade: road grade (decimal fraction).

It is noted that since the examined roundabout is installed in a flat area with a grade of less than 2 percent. As a result, the parameter of road slope was considered negligible and was excluded from consideration when applying the VSP methodology. Furthermore, the proportion of heavy vehicles and motorcycles observed was relatively small. As a result, the calculated passenger car units (PCUs) were treated as equivalent to light vehicles for the purposes of the VSP analysis.

Each second of driving is classified into fourteen distinct modes that represent various driving conditions. More specifically, VSP modes 1 to 2 correspond to deceleration modes, VSP mode 3 represents idling conditions (such as queued vehicles) or low-speed situations, while VSP modes from 4 to 14 correspond to cruising and acceleration modes.

VSP was initially calculated based on vehicular kinematic characteristics and road geometry, and then apportioned to corresponding categories that represent various driving behavior conditions [63]. Each VSP category was assigned a specific pollutant emission value, accounting for the appropriate factors for both petrol and diesel light vehicles [56,64]. The estimated share between them was calculated to be 90.1% and 8.6%, respectively [65]. The rest of the total amount was excluded from the analysis, assuming a small share for zero-emission vehicles. Pollutant emissions were initially calculated for every second and every vehicle. Finally, total emissions per vehicle route and OD were calculated and further applied for analysis.

4. Results

Figure 8 illustrates the spatial distribution of total CO_2 emissions produced for the morning peak hour in the two roundabout configurations: (a) the existing multilane roundabout, and (b) the examined turbo-roundabout. The spatial distribution of pollutant emissions is emphasized as a key factor in improving the understanding of potential road design adjustments regarding environmental considerations.

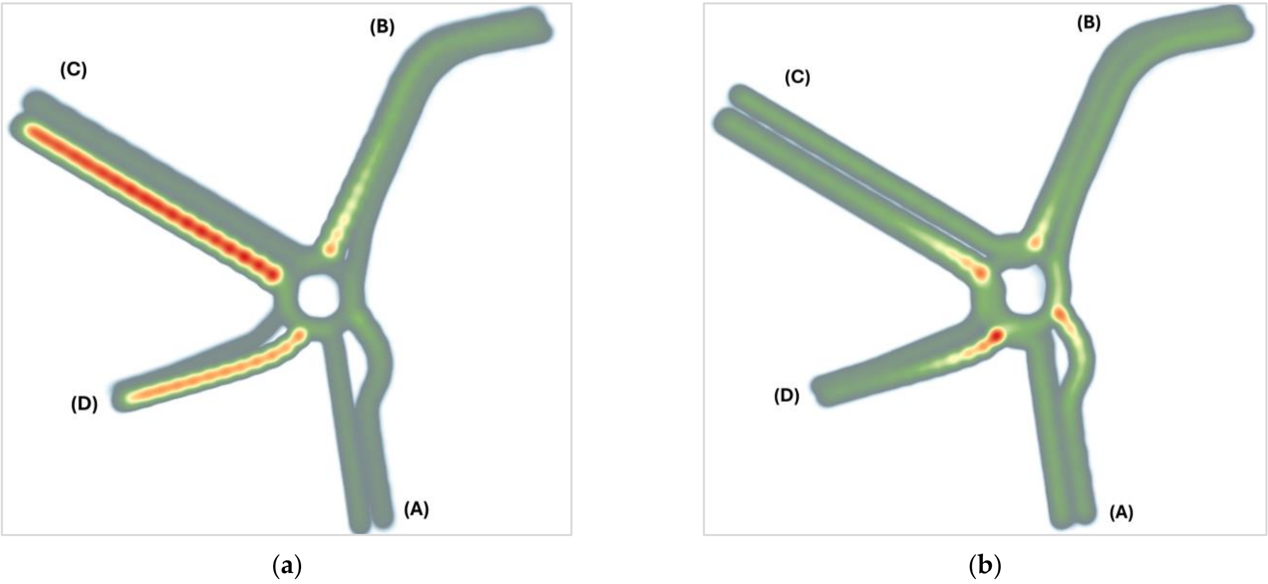


Figure 8. Spatial distribution of total CO_2 emissions produced: (**a**) existing multilane roundabout, (**b**) examined conversion into a turbo-roundabout.

In the first scenario, where a multilane roundabout is involved, traffic emissions are dispersed over a larger area, primarily concentrated in the lanes approaching the roundabout. On the contrary, the turbo-roundabout concentrates emissions primarily within the intersection layout, specifically near the approaches. These initial findings suggest that queues and traffic conditions in multilane roundabouts contribute to a wider dispersion of emissions, while more efficient traffic flow and smoother vehicle maneuvers in turbo-roundabouts lead to less emissions (Table 3) which are concentrated within the roundabout itself. Consequently, turbo-roundabouts have the potential to improve the local air quality in surrounding areas, compared to multilane roundabouts.

Table 3. Comparison of total CO_2 trip emissions [g] between the multilane roundabout and turbo-roundabout.

Trip		**Traffic Volume [PCUs]**	**CO_2 Pollutant Emissions [g]**		**Impact**
Entry	**Exit**		**Multilane Roundabout**	**Turbo-Roundabout**	
A	B	146	12,795	13,291	Increase
	C	317	27,824	35,813	Increase
	D	24	1,424	1,383	Decrease
B	A	248	33,357	19,861	Decrease
	C	323	36,875	23,473	Decrease
	D	210	30,996	17,064	Decrease
C	A	475	94,617	36,051	Decrease
	B	420	93,640	39,788	Decrease
	D	51	8,780	5,382	Decrease
D	A	84	16,634	7,257	Decrease
	B	167	39,452	21,877	Decrease
	C	84	15,137	9,585	Decrease
Total Emissions			411,531	230,825	Decrease
Weighted Emissions			51,546	26,911	Decrease

Table 3 presents the emission results from the simulation tests performed, specifically showing total carbon dioxide emissions for each O-D trip. The differences in emissions between the before-and-after scenarios are evident.

As shown, the largest differences in emissions occur for the C-A and C-B trips, while the smallest difference is observed for the A-D trips. In nearly all cases, the turbo-roundabout results in a noticeable reduction in pollutant emissions.

Statistical Analysis

Figure 9 presents the boxplot of carbon dioxide emissions recorded for the trips conducted for both multilane roundabout and turbo-roundabout.

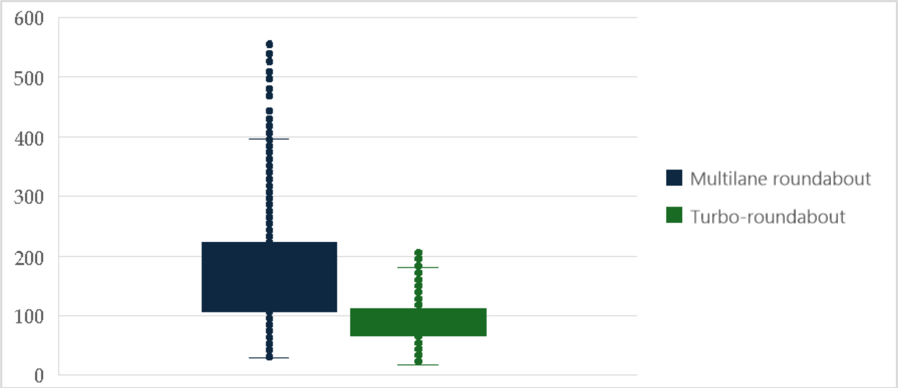


Figure 9. Boxplots of observed carbon dioxide.

According to the boxplots, it is highlighted that the range of values for the case of multilane roundabout trips is large. The observed high variability of pollutant emissions is strongly related to both aggressive and defensive driving behaviors of roundabout vehicle users.

To assess the environmental performance of the multilane roundabout and turbo-roundabout, the differences in average CO_2 emissions were analyzed using the Wilcoxon–Mann–Whitney test at a significance level of $\alpha = 0.05$. This non-parametric test was selected due to violations of the assumptions of the t-test in most cases.

Table 4 presents the results of the statistical analysis. It is noted that *p*-values in boldface indicate statistically significant differences.

Table 4. Wilcoxon–Mann–Whitney test results for differences in average CO_2 emissions [g].

Trip	Multilane Roundabout			Turbo-Roundabout			Statistic	*p*-Value
	Mean	Median	SD	Mean	Median	SD		
A-B	92.72	89.18	33.85	97.01	100.66	30.24	W = 17,915	0.087 $^{n.s.}$
A-C	98.32	96.40	31.40	102.91	101.88	31.37	W = 84,040	**0.018** **
A-D	94.94	92.11	25.62	92.20	91.91	23.83	W = 229	0.902 $^{n.s.}$
B-A	160.37	156.98	64.72	91.53	93.32	27.07	W = 31,628	**<0.001** ***
B-C	120.11	114.07	46.93	73.58	70.56	20.17	W = 67,701	**<0.001** ***
B-D	160.60	157.57	68.58	85.32	85.97	25.00	W = 26,476	**<0.001** ***
C-A	203.93	183.54	96.21	74.03	71.13	26.40	W = 129,007	**<0.001** ***
C-B	233.52	216.59	94.13	98.24	98.83	27.18	W = 90,129	**<0.001** ***
C-D	199.54	157.53	101.33	66.45	62.57	27.14	W = 3442	**<0.001** ***
D-A	207.93	203.84	62.29	96.76	97.07	31.64	W = 3150	**<0.001** ***
D-B	229.37	220.50	53.39	127.94	126.80	32.53	W = 15,869	**<0.001** ***
D-C	236.52	229.75	64.73	126.14	128.57	37.15	W = 3201	**<0.001** ***

***: Significant at 1% level; **: significant at 5% level; *: significant at 10% level; $^{n.s.}$: non-significant.

According to our findings, it can be observed that except for the trip from A to B and the trip from A to D, all other trips result in statistically significant differences in carbon dioxide emissions. To explain differences in pollutant emissions between the two types of roundabouts, the distribution of VSP categories for both multilane roundabouts and turbo-roundabouts is presented in Figure 10. VSP modes 1 to 2 correspond to deceleration modes, VSP mode 3 represents idling or low-speed situations, and VSP modes from 4 to 14 correspond to cruising and acceleration modes.

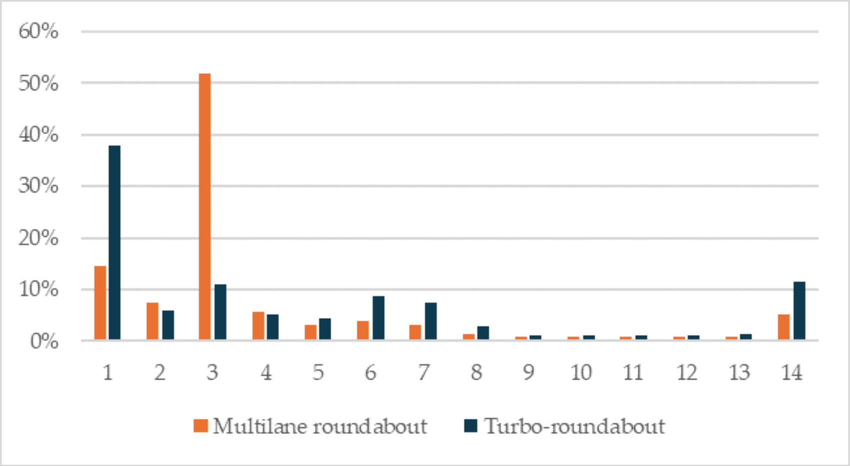


Figure 10. Distribution of VSP categories for both the multilane roundabout and the turbo-roundabout.

As for the turbo-roundabout intersection, the distributions exhibit a bi-modal pattern: higher speeds correspond to instances where drivers encountered free-flow conditions prior to approaching the intersection, while lower speeds reflect cases where drivers decelerated before entering the roundabout. Overall, the distribution of Vehicle-Specific Power (VSP) modes at the turbo-roundabout suggests typical traffic conditions. A notable proportion of vehicles fall into VSP mode 14, indicating high acceleration upon exiting the intersection, which is expected for some drivers. In contrast, at the multilane roundabout, a significant percentage of vehicles fall into VSP mode 3, representing idling or constant low-speed conditions, characteristic of saturated traffic conditions (see the maximum queue lengths per approach in Figure 7).

These variations in VSP categories, along with differences in average speeds, help explain the discrepancies in total carbon dioxide emissions. Emissions are largely influenced by trip duration and traffic efficiency, both of which are enhanced by the improved geometric configuration of the turbo-roundabout.

5. Conclusions

The European Union seeks to attain zero carbon dioxide emissions from new passenger vehicles, necessitating a shift from internal combustion engine automobiles to zero-emission alternatives. Despite initiatives aimed at advancing electric cars and active transportation, issues like traffic congestion and diverse vehicle usage underscore the necessity for coordinated, multimodal strategies. Redesigns of road systems aimed at reducing air pollution must be executed judiciously to prevent unexpected repercussions, such as the rebound effect, and to mitigate pollution hotspots where carbon monoxide and particulate matter may accumulate. The design of roundabouts affects vehicle emissions, owing to the acceleration and deceleration linked to free-flow circumstances. Turbo-roundabouts can optimize traffic flow and mitigate congestion by merit of their improved geometric design, hence facilitating continuous movement and substantially decreasing polluting emissions.

Our case study on the virtual reconfiguration of an existing multilane roundabout into a turbo-roundabout demonstrates potential improvements not only in traffic capacity, road safety, and aesthetics, but also in reducing vehicle emissions by up to 44%. Specifically, emissions were reduced by up to 44% across both the intersection and the broader area encompassing the approaches, and by up to 23% at the intersection itself. Analysis of morning peak hour traffic reveals statistically significant reductions in carbon dioxide emissions, attributed to the improved geometric layout. In-depth Vehicle-Specific Power (VSP) analysis highlights that carbon dioxide emissions are strongly influenced by trip duration and traffic efficiency, both of which are positively impacted by the enhanced design of turbo-roundabouts.

The novelty of this study lies in its use of Vehicle-Specific Power (VSP) analysis, which reveals the strong correlation between emissions and trip duration as well as traffic efficiency—both of which are positively affected by turbo-roundabout designs. This study adds to a growing corpus of research showing the importance of turbo-roundabouts and has important implications for environmental- and road infrastructure-design approaches. It highlights the environmental benefits of turbo-roundabouts and emphasizes the importance of road infrastructure redesigning in mitigating pollutant emissions.

This study offers significant insights into the environmental and traffic efficiency advantages of turbo-roundabouts; nonetheless, limitations must be acknowledged. The analysis relies on a case study of a multilane roundabout and specific origin–destination patterns, thus constraining the generalizability and applicability of the findings to other locations with varying traffic circumstances. The results may not completely reflect the discrepancies in emission reductions that might arise in areas with varying traffic patterns.

Moreover, the unfamiliarity of turbo-roundabouts to drivers who encounter them for the first time can result in higher values in gap-acceptance parameters and therefore a reduction in the estimated capacity, particularly during the initial years of operation. The potential impact of limited familiarity with a type of intersection has not been considered in this analysis.

Further research is necessary to validate the conclusions that can be drawn from this study. More specifically, future research should consider various trip patterns to develop a holistic understanding of the contribution of road geometry and turbo-roundabout design to pollutant emission reduction.

Further investigations should look into a wider array of travel patterns and traffic behaviors to achieve a more thorough understanding of how road geometry, specifically turbo-roundabout design, affects reductions in pollutant emissions. Moreover, subsequent research should evaluate the enduring environmental effects and the cost–benefit analysis of using such designs across diverse traffic scenarios and geographical regions. Finally, this study mainly depends on virtual simulation data, which, however informative, may not encompass all real-world complexities. Field experiments are crucial for validating the accuracy and application of the findings in actual-life situations.

Policymakers may utilize these data to inform decisions on sustainable transportation infrastructure, promoting the implementation of turbo-roundabouts and analogous designs to fulfill environmental and safety objectives. The spatial distribution of pollutant emissions emerges as a critical factor in understanding the environmental implications of road design. By unveiling the factors of road geometry mitigating pollutant emissions, the present study can assist authorities and policymakers with regard to the potential of alternative types of modern roundabouts and enable them to take specific actions.

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