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A multi-objective method for large multi-lane roundabout design through microscopic traffic simulation and SSAM analysis

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A B S T R A C T

Urban traffic congestion poses a significant challenge, impacting both economic efficiency and environmental sustainability. Roundabouts, recognized for their ability to improve traffic flow and reduce collisions, have become a focal point in traffic management strategies in urban areas. Different types and sizes of single and multi-lane roundabouts can be used, including conventional and innovative roundabouts with small, medium or large size diameters. Many optimization models are available for designing conventional roundabouts but not large roundabouts. To partially cover this gap, the present paper introduces a novel approach integrating simulation-based analysis with a goal programming method to optimize large roundabout design. By leveraging advanced traffic simulation tools like AIMSUN Next and Surrogate Safety Assessment Models (SSAMs), this methodology evaluates multiple design scenarios to enhance traffic flow, safety, and environmental performance. A case study of a complex large roundabout in the Italian greenest and sustainable city demonstrates the efficacy of this methodological approach. The findings provide valuable insights for traffic and highway engineers, emphasizing a data-driven, holistic approach to sustainable traffic management and roundabout optimization.

1. Introduction

Urban traffic congestion continues to be a pressing challenge, significantly impacting economic efficiency and environmental sustainability. Roundabouts, widely recognized for their potential to enhance traffic flow and reduce collision rates, have become a focal point for urban traffic management strategies. However, optimizing roundabout design requires a nuanced understanding of traffic dynamics and the interactions between various design parameters and traffic behaviors. This paper proposes a novel approach that integrates simulation-based analysis with mathematical optimization techniques to identify the most effective modifications for large roundabout configurations. This methodology leverages mathematical models' precision and simulation's dynamic testing capabilities, aiming to bridge the gap between theoretical optimization and real-world applicability. This integrated approach provides a robust framework for urban planners and traffic engineers to enhance the efficiency and safety of roundabouts, thereby improving overall traffic management in urban settings.

This research describes a novel approach integrating simulation-based analysis in AIMSUN and SSAMs environments with goal programming to optimize large roundabout design. A case study in Trento, Italy, is considered. The rest of the article is organised as follows. In the Section 1.1 a brief literature review on design the main characteristics of modern roundabouts and the main used procedure for optimization their design is given. Section 2 the concept of the Multi-Objective Optimization Model is introduced. Section 3 presents the case study and the proposed layouts for the large multi-lane roundabout. Section 4 describes discussions and results. Section 5 gives the conclusions of this study.

1.1. Literature review

Following this brief introduction, the paper will proceed with a comprehensive review of the literature, exploring existing methods and technologies in roundabout analysis and optimization, highlighting the need for innovative solutions combining theoretical and empirical insights.

Roundabouts are increasingly recognized for their ability to improve traffic flow, safety, and environmental impacts compared to traditional signalized intersections [1-3]. Properly designed roundabouts can significantly reduce vehicle speeds through geometric parameters such

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Nomenclature

a(n)	maximum acceleration for the vehicle n in its current location [m/s^2]
α	level of significance
c	construction cost [€]
c'	maximum permissible construction cost [€]
CAVs	connected and automated vehicles
d	mean delay [s/veh]
d'	maximum permissible mean delay [s/veh]
d(n)	maximum deceleration desired of the n-th vehicle [m/s^2]
GEH	Geoffrey E. Havers index
GIS	Geographic Information System
GP	Goal Programming
G1-G4	identify and define the goals
θ	conflict angle between a couple of vehicles
θ_1	rear end threshold angle
θ_2	crossing threshold angle
i	i th criterion
ITS	Intelligent Transportation Systems
j	j-th roundabout's layout
k	mean vehicle density [veh/km/lane]
k'	permissible vehicle density [veh/km/lane]
MNE	mean normalized error
MOTPs	multi-objective transportation problems
n	n-th vehicle
O/D Matrix	Origin /Destination traffic matrix [veh/h]
p	number of conflict points [n°]
p'	maximum permissible conflict points [n°]
PET	Post-Encroachment Time [s]
P_r	probability of the difference between the real the simulated values of a given traffic variable is less than a prefixed acceptable difference
QGIS	Quantum Geographic Information System
RMSE	root mean square error
RMSNE	root mean squared normalized error
$s(n-1)$	length of the vehicle $(n-1)$ [m]
SSAM	Surrogate Safety Assessment Module
SSMs	Surrogate Safety Measures
t	time instant [s]
T_j	target level
T_r	drivers' reaction time [s]
TTC	Time-to-Collision [s]
v	space mean speed [m/s or km/h]
v'	minimum acceptable space mean speed [m/s]
v_{ij}	value of goal i for the design j
V(n, t)	speed of the vehicle n at the time instant t [m/s]
V*(n)	desired speed of the vehicle (n) in its current location [m/s]
w_i	denotes the weight assigned to the criterion i
x_i	simulated queue length [veh]
x(n, t)	position of the vehicle n at time t [m]
y_i	observed queue length [veh]
$Z_{ij}(\cdot)$	Z-score normalization of the criteria i

as the deviation angle, which is crucial for controlling vehicle trajectories and enhancing safety [1]. Roundabouts are often more efficient in handling large volumes of traffic with respect to two-lane stop-controlled intersections, reducing the number of stops and delays experienced by vehicles, thus contributing to smoother traffic flow and potentially reducing congestion [2,3]. A simple criterion for choosing the proper intersection control type as a function of two-way peak-hour volumes on the major and minor streets is given in Fig. 1.

Comparative assessments of different roundabout designs, including modern, elliptical, and turbo roundabouts, have shown that while all types offer safety and environmental benefits over signalized intersections, turbo roundabouts excel in safety and functionality at low to medium traffic volumes and in the case of high right-turning percentages manoeuvres [4,5]. Alternative roundabout designs, such as two-level roundabouts, offer solutions for urban and suburban areas with space constraints, providing unique advantages in terms of capacity and safety [6]. Technological advancements in traffic management systems for roundabouts, especially with the future integration of connected and automated vehicles (CAVs) [7] can significantly increase throughput and reduce control delays, offering a promising approach to optimizing roundabout performance [8,9]. The integration of autonomous vehicles into roundabout traffic will also require sophisticated methods for inferring the intentions of surrounding vehicles to ensure safe and efficient entry and navigation through road intersections [10]. The design and implementation of roundabouts of varying sizes are influenced by a multitude of factors, each contributing to the overall safety, efficiency, and environmental impact of the traffic management solution. One primary consideration is the geometric parameters, such as the inscribed circle diameter and the angle between opposite legs, which directly affect the deviation angle and, consequently, the speed control and safety of the roundabout [1-3]. The configuration of the roundabout, whether it is a full, three-leg, or four-leg layout, also significantly impacts the factors contributing to both severe and less severe crashes, highlighting the need for configuration-specific safety measures [11]. A comprehensive comparison of conventional and innovative roundabouts based on functional, environmental, and economic aspects helps identify the most suitable types for specific traffic demand conditions [6]. An LCA procedure for assessing the global roundabout impact during the life cycle, based on the study of pavement materials (subgrade, embankment, surface layer), maintenance and operational activities and relevant transport activities for construction and maintenance of traditional and innovative intersections (conventional double lane roundabouts, turbo-roundabouts and flower –roundabouts) is explained in [12].

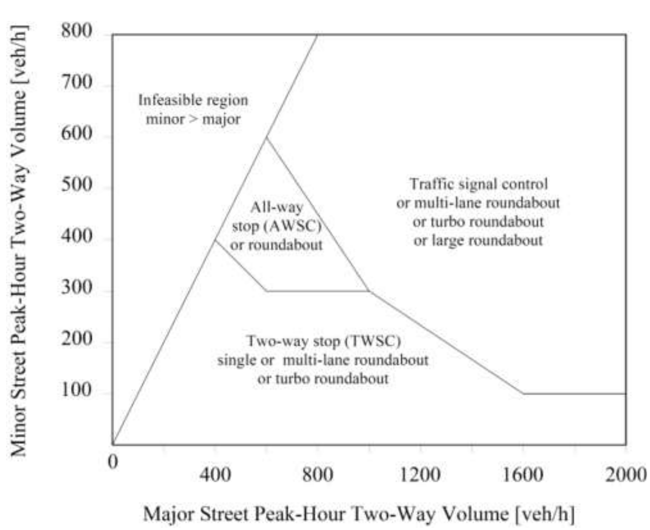


Fig. 1. Criterion for choosing the intersection control type in function of two-way peak-hour volumes on the major and minor streets (adapted from [4]).

Roundabouts, as a crucial component of modern urban road networks, exhibit various scales in design, capacity, safety, environmental impact, and driver behaviour metrics.

The size of modern roundabouts varies significantly across these types, from compact single-lane roundabouts with diameters between 26 and 40 m, to mini-roundabouts with traversable islands and diameters between 13 and 25 m, and larger roundabouts (40–60 m) designed to accommodate higher traffic volumes [13]. Roundabout sizes and designs exhibit significant variation across different countries and regions, influenced by local traffic regulations, safety standards, and urban planning objectives. In Europe, for instance, "standard" roundabouts can be characterized by varying levels of safety, capacity, and sustainability, prompting a reevaluation of design practices based on international experiences [13,14]. The size of roundabouts significantly influences their functionality, safety, and environmental impact. Smaller roundabouts are particularly effective in urban areas where space is limited and can handle up to 18,000 vehicles per day [11,13]. Conversely, larger roundabouts can accommodate higher traffic volumes more efficiently. The introduction of right-turn bypass lanes in conventional roundabouts has been identified as a cost-effective measure for improving traffic flow and reducing emissions when traffic entering the roundabout exceeds 2000 vehicles per hour [12].

The concept of "large-scale roundabouts" encompasses their physical dimensions and impact on traffic flow, safety, and urban development. The rapid urbanization and the consequent rise in large-scale construction projects underscore the importance of efficient traffic management systems, where large roundabouts can play a pivotal role in mitigating traffic accidents with respect to interchanges [15]. Moreover, the scale of roundabouts is not merely a matter of physical size but also involves their role within the larger transportation system and urban areas. Large-scale roundabouts can be considered part of broader urban and infrastructural interventions, similar to large-scale construction projects that unify multiple subprojects and cover extensive site areas, reflecting rapid urbanization and efficient traffic management solutions [16]. Large roundabouts sometimes offer a multitude of benefits, including enhanced safety, improved traffic flow, and environmental advantages [17]. They are engineered to accommodate higher traffic volumes. As the focus transitions to the role of simulation in roundabout design, it becomes essential to rigorously evaluate these impacts across a range of traffic conditions. Simulation tools, such as AIMSUN, offer sophisticated platforms for the visualization and prediction of traffic behaviors, thereby enabling engineers to meticulously refine roundabout designs prior to their implementation. This seamless transition effectively integrates practical considerations with theoretical frameworks, enhancing roundabouts' overall functionality. Simulation has become a pivotal tool in traffic engineering, enabling engineers and urban planners to visualize and predict traffic flow under various conditions without the need for physical trials. By simulating traffic scenarios, including complex roundabout systems, planners can assess the impact of different designs on traffic efficiency and safety. This proactive approach allows for adjustments to be made in the design phase, reducing costs and potential real-world traffic issues. The use of simulation software in the study of roundabouts particularly aids in optimizing traffic circulation patterns, assessing vehicle-pedestrian interactions, and enhancing overall road safety [18-20]. This methodological approach is critical in developing solutions that accommodate growing urban populations and the dynamic demands of modern transportation networks.

Microscopic simulation can be used also in the case of smart roads and intersections [21]. AIMSUN stands out as a sophisticated microscopic traffic simulator designed to enhance the assessment of several transportation systems, including the Intelligent Transportation Systems (ITS) [21,22]. The application of AIMSUN in traffic simulation studies has demonstrated significant advancements in understanding and improving urban mobility, traffic flow, and environmental impacts. In another study, AIMSUN was utilized to estimate vehicle emissions at urban roundabouts [23,24]. Similar research employed modeling and optimization software, including AIMSUN, to enhance traffic condition quality and sustainable urban transportation, highlighting its role in smart urban planning [24]. In [25] the authors explored the impact of side friction factors on traffic stream performance using AIMSUN, indicating its effectiveness in simulating complex urban traffic scenarios and improving traffic management strategies. Other interesting applications are on the speed profiles, pollutant and noise emissions [26].

Surrogate Safety Assessment Models (SSAMs) are pivotal in evaluating road safety by estimating potential collision points without relying on historical crash data, which can be scarce and challenging to collect, especially in mixed-traffic environments [27]. These models leverage Surrogate Safety Measures (SSMs) as proxies to traditional crash data, offering a proactive approach to identify and mitigate safety risks before real accidents occur [28]. The development of novel SSMs, such as the Anticipated Collision Time (ACT) and its derivatives, further enhances the ability to capture the overall crash risk [29,30], including for specific scenarios like Powered Two Wheelers (PTWs) in urban environments [31].

Multi-objective optimization (MOO) modeling can be applied in the optimization process of the roundabout design taking into consideration various criteria such as safety, capacity, delay and environmental impact. This approach employs advanced algorithms to balance these objectives effectively, ensuring that the roundabout design achieves an optimal compromise between capacity and safety. A multi-criteria and simultaneous multi-objective optimization model approach that considers geometry, traffic efficiency, and safety can optimize the design of urban unsignalized single-lane roundabouts, thereby enhancing safety [32].

Goal Programming (GP) is a multi-criteria decision-making tool that addresses problems involving conflicting objectives by finding a solution that minimizes the deviations from a set of predefined goals. Originating in the 1950s, GP has seen widespread application across various fields due to its mathematical simplicity and modeling elegance, making it a popular choice for solving applied problems in engineering, management, and social sciences [33]. It is particularly useful in situations where decision-makers must aggregate several conflicting and incommensurable factors, as often encountered in accounting, to decide on the best compromise [34]. The versatility of GP is further highlighted by its application in diverse scenarios, from optimizing production policies in companies to ensure customer demands are met efficiently [35], to determining the optimal harvest volume in forest management for multipurpose objectives [36]. Goal programming (GP) is a pivotal optimization technique in addressing transportation problems, especially when dealing with multiple objectives and uncertainties inherent in transportation logistics and infrastructure planning. The essence of GP in transportation is to find a compromise solution that best meets a set of predefined goals or objectives, considering the complexities and uncertainties of real-world scenarios. In the realm of transportation, uncertainties such as fluctuating demand, variable transportation costs, and environmental conditions necessitate the use of fuzzy goal programming and robust goal programming approaches. These methods allow decision-makers to handle data uncertainty effectively, ensuring that the transportation plans are both realistic and flexible [37,38]. For instance, fuzzy goal programming is utilized to manage uncertain parameters in multi-objective transportation problems (MOTPs), converting uncertain data into a more manageable form for optimization [39]. Similarly, robust goal programming combines robust optimization with goal programming to address data-driven applications, enhancing the decision-making process in transportation rate setting by incorporating risk preferences regarding parametric variability [40]. In the context of roundabout optimization, goal programming can be instrumental in addressing various objectives such as minimizing congestion, reducing accident rates, optimizing construction and maintenance costs, and enhancing overall traffic flow efficiency. The application of GP in engineering and design problems, showcases its robustness and efficiency in finding high-quality solutions within short computational times [41], a feature highly beneficial in the dynamic context of roundabout traffic management. Meanwhile, goal programming in multi-criteria decision-making is explored under certainty and extended to uncertain problems, presenting a novel decision rule that can be applied across different decision-maker attitudes [42].

Numerous dimensional, geometric, and traffic regulation factors must be optimised to build safe and efficient roundabouts. Many optimization models based on traffic simulations have been used to study conventional roundabouts but not large roundabouts. To partially cover this gap and capture the relationship between geometry, efficiency and safety of large roundabouts, this paper proposes a specific methodological approach based on MOO and GP. The procedure is applied to a large multi-lane complex roundabout in operation in Trento (Italy) [32, 43-45]. In short, the main novelties and contributions of this research are:

- evaluate the relationship between geometry, efficiency and safety of large roundabouts;
- apply a Multi-Objective Method to a Large Roundabout Design in order to obtain the scenario with the best Measure of Effectiveness (MOE), safety metrics and, at the same time, the lowest possible construction costs.

2. Methodology

In transportation planning, decision-makers often face the challenge of balancing multiple, often conflicting, objectives such as minimizing travel time, costs, and safety risks while maximizing service quality and system efficiency. This study introduces a multi-objective optimization model that employs Z-score normalization and weighted sum scoring to analyze various layouts and simulations of a roundabout, providing a systematic approach for optimal decision-making to select the best design for requalifying geometrically existing large roundabouts. The proposed method was applied to a case study in the urban context of Trento (Italy).

2.1. Multi-Objective optimization model and assumptions

The dataset comprises five attributes: space mean speed, delay, vehicle density, number of collision points, and construction cost. These attributes reflect some of the most important aspects that affect both operational performance and safety of transportation systems.

The multi-objective optimization model is formulated as follows:

Objective Function:

$$\text{Maximize} \sum_{j}^{n} \sum_{i}^{m} x_j \left(w_i z_{ij} \right) \tag{1}$$

Where x_j is the binary variable to determine the best roundabout layout. $Z_{ij}(\cdot)$ denotes the Z-score normalization of the criterion i (space mean speed (v), mean vehicle density (k), mean delay (d), safety (number of conflict points (p)), and construction cost (c)) for the roundabout's layout j and w_i denotes the weight assigned to the criterion i, reflecting its relative importance in the overall evaluation. When working with an optimization model that addresses multiple objectives with varying units and scales (like safety, cost, and speed), a common approach is normalising these values. Normalizing the object variables ensures each objective contributes equitably to the overall solution, preventing any single metric from disproportionately influencing the outcome due to its scale or units. For this study, the values of p_j and n_j will be normalized by the Z-score Normalization method, whose general equation is:

$$Z = \frac{x - \mu}{\sigma} \tag{2}$$

Where:

- Z is the normalized value;
- x is the actual value that it needs to normalize;
- μ is the mean of the sample;
- σ is the standard deviation of the sample;

The constraints are detailed below:

- Ensure only one roundabout's layout is selected:

$$\sum_{j} x_j = 1 \tag{3}$$

- Ensure compliance with the minimum acceptable space mean speed (v'), permissible vehicle density (k'), maximum permissible mean delay (d'), and maximum permissible conflict points (p') and construction cost (c'):

$$\sum_{j} x_j \cdot v_j \geq v' \tag{4}$$

$$\sum_{j} x_j \cdot k_j \leq k' \tag{5}$$

$$\sum_{j} x_j \cdot d_j \leq d' \tag{6}$$

$$\sum_{j} x_j \cdot p_j \leq p' \tag{7}$$

$$\sum_{j} x_j \cdot c_j \leq c' \tag{8}$$

2.2. Goal programming

This section elucidates the application of Goal Programming (GP) in the optimization of large roundabout designs, as evidenced by a case-specific example, thereby emphasizing its practical relevance. The resolution of multiple conflicting objectives—such as the minimization of delays and the enhancement of safety—is demonstrated through a scenario analysis conducted within the framework of the Trento case study, utilizing the GP model. This model employs GP to ascertain the optimal roundabout design by integrating a variety of factors, including traffic distribution, vehicle types, and accident probabilities. The GP offers a balanced resolution among these objectives, thereby underscoring its practical applicability in intersection design.

To utilize goal programming for selecting the optimal roundabout design based on various criteria such as safety (collision points), cost, vehicle speeds, density, and delay, the model needs to be structured to consider all these aspects simultaneously. In this paper, a novel optimization model based on goal programming is introduced to enhance the design and functionality of roundabouts. This approach systematically addresses the complex trade-offs between safety, cost, vehicle speeds, density, and delay by integrating multi-objective goal programming [46,47]. The model prioritizes achieving an optimal balance among these competing objectives, thereby proposing roundabout designs that are efficient in terms of capacity and promote safety. This framework is demonstrated through case studies that highlight its practical implications and effectiveness in planning scenarios. The model is detailed below.

Let x be a binary decision variable where:

$$x_i = 1 \text{ if design j is selected} \tag{9}$$

$$x_i = 0 \text{ otherwise.} \tag{10}$$

Identify and define the goals:

- G1 : Maximize space mean speed (11)

- G2 : Minimize vehicle density (12)
- G3 : Minimize delay (13)
- G4 : Minimize the collision points (i.e. Maximize safety) (14)
- G5 : Minimize the construction cost (15)

Assign weights $w_1, w_2, \ldots, w_5$ to each goal based on their importance. Collect or estimate data for each goal for every design:

v_{ij} represents the value of goal i for design j (16)

For each goal, there is a target level T_j and positive and negative deviation variables p_{ij} and n_{ij} will be introduced to capture the deviation from the goal levels. The aim is to minimize undesirable deviations and maximize desirable deviations. For goals minimization (e.g., delay, speed, cost):

$$v_{ij} + n_{ij} - p_{ij} = T_j \tag{17}$$

For maximization goals (e.g., vehicle speeds, capacity, etc.):

$$v_{ij} - n_{ij} + p_{ij} = T_j \tag{18}$$

The objective function in goal programming is to maximize the weighted difference of these deviations:

$$\text{Max} \sum_j \sum_i x_j \left(w_i \cdot p_{ij} - w_i \cdot n_{ij} \right) \tag{19}$$

w_i is the weight for the criteria i. Also, for this model, the values of p_{ij} and n_{ij} will be normalized by the Z-score Normalization method.

w_j^+ and w_j^- are weights for the positive and negative deviations, reflecting the penalty for underachieving or overachieving relative to T_j. Also, for this model, the values of p_{ij} and n_{ij} will be normalized by the Z-score Normalization method:

Constraints:

- Ensure only one design is selected:

$$\sum_i x_i = 1 \tag{20}$$

- Ensure compliance with the minimum acceptable space mean speed (v'), permissible vehicle density (k'), mean delay (d'), and maximum permissible conflict points (p') and construction cost (c'):

$$\sum_j x_j \cdot \left(v_{ij} + n_{ij} - p_{ij} \right) \leq v' \tag{21}$$

$$\sum_j x_j \cdot \left(v_{ij} + n_{ij} - p_{ij} \right) \leq k' \tag{22}$$

$$\sum_j x_j \cdot \left(v_{ij} + n_{ij} - p_{ij} \right) \leq d' \tag{23}$$

$$\sum_j x_j \cdot \left(v_{ij} - n_{ij} + p_{ij} \right) \leq p' \tag{24}$$

$$\sum_j x_j \cdot \left(v_{ij} + n_{ij} - p_{ij} \right) \leq c' \tag{25}$$

Finally, it is requested that the deviations must be appropriately linked to the selected design:

$$p_{ij},\ n_{ij} \geq 0\ \forall i \text{ and } \forall j. \tag{26}$$

x_j should be linked to p_{ij} and n_{ij}, so deviations are considered only if $x_j = 1$

It is worth underlining that apart from the applications outlined above, goal programming has also shown adequate prospects for an integrated disaster management setup. For example, it is applied smoothly in integrated relief distribution and early-stage network restoration after a disaster. This application points to the possibility of simultaneously dealing with numerous, often conflicting, logistical and infrastructural recovery goals, thus enabling quick and cost-effective decision-making critical in disaster response operations [47]. In conclusion, research proves that goal programming is widely applied beyond usual traffic and city planning and in areas where flexible and multi-dimensional decision frameworks are needed.

3. The case study

Located in the stunning Trentino region of northern Italy, Trento is a charming city renowned for its rich history, picturesque landscapes, and vibrant cultural scene. As the capital of Trentino, it boasts a seamless blend of medieval architecture and modern amenities, making it a captivating destination for travellers and a dynamic hub for transportation and urban mobility research. Trento is the city in Italy with the best urban sustainability in terms of transport, energy and environment. According to recent statistics, Trento is also the greenest city in Italy. The implementation and design of roundabouts in Trento can benefit significantly from a comprehensive understanding of various factors influencing their safety, efficiency, and public perception. Using advanced spatial analysis techniques within QGIS, high-risk areas for driving incidents in Trento were identified, including the 54 roundabouts in operation. The Fig. 2(a) illustrates traffic accidents across the city of Trento. A notable feature highlighted in the map is the “Svincolo TN Centro” circled in red, which appears to be a critical traffic junction with a high incidence of accidents.

This interchange’s prominence on the map underscores its significance as a potential hotspot for traffic-related issues. The dense clustering of accidents around this area (Fig. 2b) suggests that it may be a focal point for targeted traffic safety interventions. In fact, between 2003 and 2020, the intersection area experienced a total of 350 accidents; the proportion between the roundabout accidents and the total accidents in the city ranged from 5 % to 15 % in the period 2003 to 2020.

Addressing the underlying factors contributing to the high accident rate at the large roundabout “Svincolo TN Centro” could significantly improve overall traffic safety for the city. The insights derived from such geospatial analysis are crucial for urban planners and policymakers aiming to reduce accident rates and enhance transportation infrastructure efficiency.

In this section, the methodology delineated in Sect. 2 is meticulously applied to the specific case of the "Svincolo TN Centro" roundabout located in the urban area of Trento with a speed limit of 50 km/h.

This comprehensive approach integrates simulation techniques and two multi-objective mathematical models, which evaluate pivotal criteria such as safety, density, delay, speed, and cost. By employing these models, extensive simulations of various design alternatives were conducted. This rigorous process facilitated the identification of the most effective redesign strategy, aimed at significantly enhancing both safety and operational efficiency at this high-risk location. The precise application of these data-driven methodologies provides robust, evidence-based recommendations, crucial for advancing road safety initiatives in Trento. The current large multi-lane roundabout is constructed on two elevation levels and exhibits the following primary geometric features:

a) at the lower level, there is an irregularly shaped two-lane roundabout with a maximum diameter of around 160 m. The roundabout includes seven entries, as depicted in Fig. 3:

Fig. 2. a) Accident distribution on the road network; b) Accident locations in the roundabout "Svincolo TN Centro".

Fig. 3. Current layout (i.e. baseline Scenario) of the analysed large roundabout in Trento.

■ Entry 1: an arm from the SS 12 road, 4.00 m wide;
■ Entry 2: a 5.00-meter-wide lane from the A22 highway toll booth;
■ Entry 3: three lanes, each 3.50 m wide, from the Gardesana “SS 45bis” road;
■ Entry 4: a 3.50-meter-wide lane from the small roundabout “Doss Trento”;
■ Entry 5: an arm from the south, from the "SS 12″ road, 4.00 m wide;
■ Entry 6: a 4.00-meter-wide lane from the S. Giorgio bridge;
■ Entry 7: an entry from the north, entering the circular carriageway from the "SS 12″ road, 4.50 m wide.

b) on the elevated section of the interchange, the SS 12 road includes its respective entry and exit ramps from the main roundabout.

Additionally, in close proximity to the interchange, there is the S. Giorgio bridge, which consists of two lanes (one per direction), each 3.25 m wide. Nearby is the “Cristo *Re*” one-lane roundabout, with an outer diameter of 30 m, featuring a single-lane ring, four entries, and five exits (cf. Fig. 3).

The road network map of Trento was created by importing Geographic Information System (GIS) data and a 1:5000 scale aerial photograph into the AIMSUN microscopic simulation software. Alignment and section of roads were adapted to be in accordance with real geometry. Attribute data of each road (e.g. legal speed, number of lanes, lane width, give way signs, traffic signal cycles, pavement markings, pedestrian crossings, etc.) has been obtained by GIS and field survey. Fig. 3 shows the road network modeled in AIMSUN Next (vertical direction indicates the geographic "South-North" alignment) used to simulate the baseline Scenario 0 (current Scenario) and the project Scenarios. Table 1 gives the Origin–Destination matrix (O/D Matrix) of the peak-flow period within the peak hour 17:00–18:00 referred to centroids depicted in Fig. 3. The 13 centroids of Fig. 3 represent the origin and/or destination of trips of the transportation network under analysis referred to O/D traffic matrix, having 13 columns and 13 rows. Centroid connections are used to introduce flow in the road network. The O/D Matrix was obtained from the traffic data of the Plans for Urban Mobility Actions of Trento, integrated by traffic sampling obtained from smart cameras.

3.1. Project scenarios

Specific design interventions have been studied to enhance the traffic performance and safety of the existing large roundabout. These interventions aim to improve the capacity and level of service at the examined roundabout and its encompassing network. Three different scenarios were analysed as follows (Figs. 4 and 5):

- Scenario 1: represents the primary "Project Scenario" (Fig. 4);
- Scenario 2: it consists of the "Project Scenario” plus a right-turn bypass lane (Fig. 5);
- Scenario 3: it consists of the "Project Scenario” with a widening of the carriageway of the San Giorgio bridge (two exit lanes instead of just one as in the basic scenario) (Fig. 5).

Scenario 1 involves transforming the current irregular shape of a large roundabout into a multi-lane circular roundabout with an inscribed circle diameter of 118 m (Fig. 4). This upgrade is designed to moderate vehicle speeds and reduce collision severity. The configuration includes dedicated lanes for different directions, including a tunnel connecting SS 45bis and SS 12 roads directly. This underground road is designed to redirect traffic away from congested urban roads, minimizing environmental impact while providing a direct, unobstructed path for vehicles. From a safety perspective, the bypass removes high-speed traffic from pedestrian-heavy areas in the South area of the roundabout, significantly lowering the risk of accidents involving non-motorized users. Advanced safety features within the tunnel, such as comprehensive lighting, emergency exits, and ventilation systems, ensure a secure environment for motorists.

Scenario 2 proposes constructing a new right-turn bypass tunnel connecting the roads SS 45bis and SS 12. Scenario 3 focuses on expanding the carriageway on Via Druso Livio and upgrading the San Giorgio Bridge in the Cristo *Re* locality. This Scenario aims to resolve bottlenecks caused by narrow road and bridge sections, which increase delays and accident risks. Proposed enhancements include additional lanes, improved lane markings, structural reinforcements for the bridge, and new pedestrian pathways. The total construction cost of each scenario is summarized in Table 2.

Microsimulation predicts significant improvements in traffic flow, reduced travel times, and increased capacity to accommodate peak traffic volumes.

For each of the above-mentioned scenarios, traffic microsimulations were run to identify the most appropriate roundabout layout which maximizes the key performance parameters. To take into consideration the new geometric configuration of the roundabout in project scenarios, the O/D Matrix was rearranged after traffic assignment, as shown in Table 3.

3.2. Traffic simulations

Microsimulations are employed to estimate the behavior of different configurations of road networks, traffic regulation systems or intersection types and layouts through stochastic experiments to compare them with alternative solutions to find the optimal one.

Many types of microsimulation software are available today. The most well-known are Vissim, AIMSUN, Paramics and SUMO. In this research, the AIMSUN Next software is used to analyze the geometric scenarios of Figs. 4 and 5 under the traffic demand summarized by the origin-destination matrix of Table 1. For traffic simulations of the

Table 1
Origin-destination matrix for the baseline scenario (cf. Fig. 3) – Time interval 17:00–18:00.

O/D	1	2	3	4	5	6	7	8	9	10	11	12	13
1	0	0	253	0	400	30	150	147	0	0	20	0	0
2	0	0	246	0	20	24	288	20	0	0	2	0	0
3	0	0	0	0	10	40	250	50	0	0	170	0	0
4	0	0	190	0	20	10	150	50	0	0	50	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	10	0	8	0	330	5	0	0	327	0	0
7	0	0	145	0	152	98	0	0	0	0	365	0	0
8	0	0	150	0	0	139	102	0	0	0	66	0	0
9	0	0	0	0	0	0	0	0	0	1594	0	0	0
10	0	0	0	0	0	0	0	0	2049	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	0

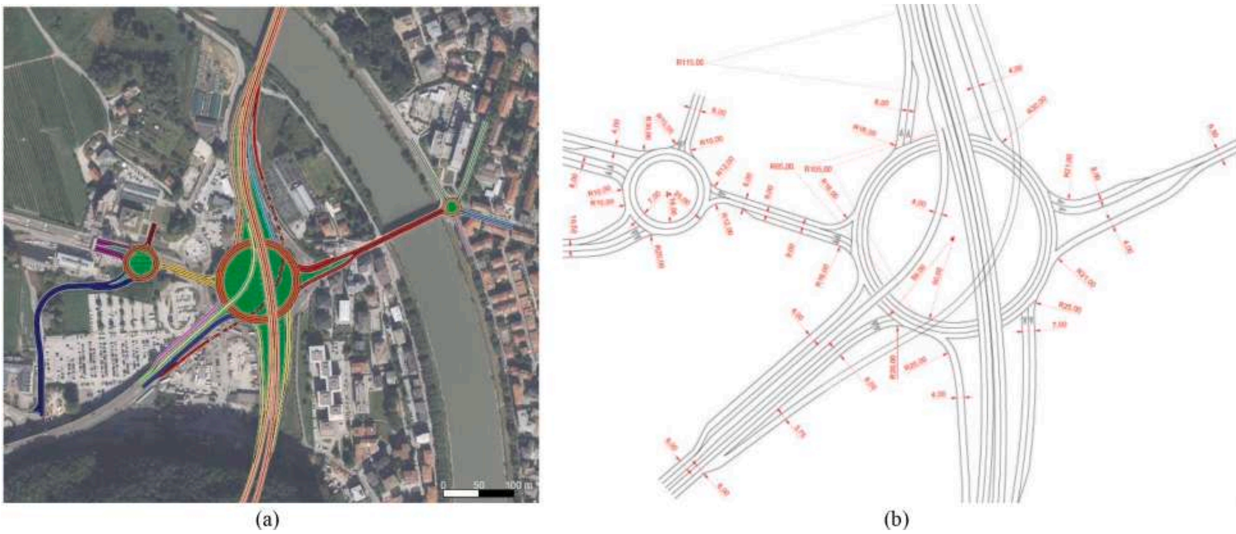


Fig. 4. Layout of the project Scenario 1 and dimensions (Roundabout 1, $R = 21.5$ m; Roundabout 2, $R = 56.0$ m).

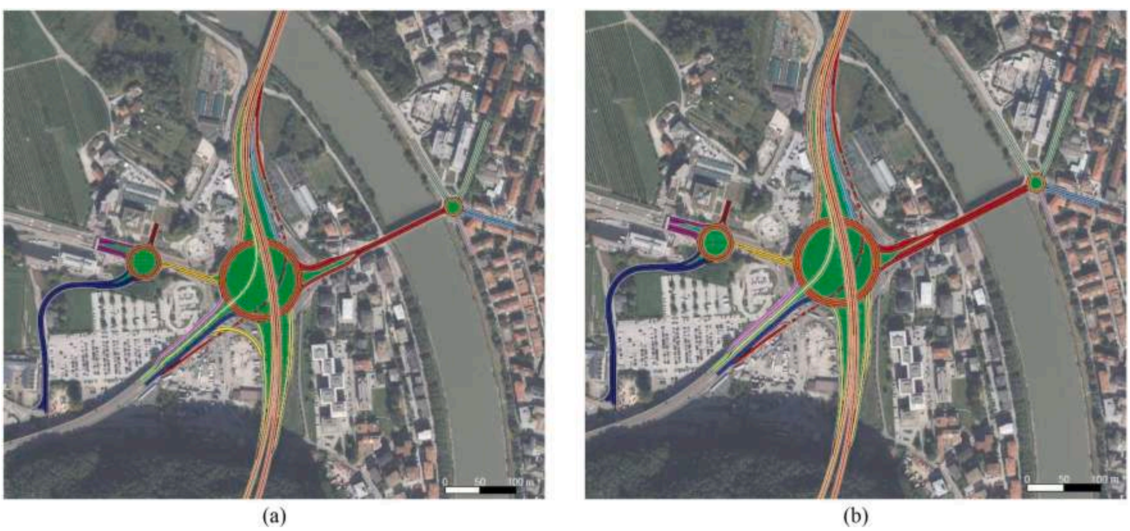


Fig. 5. Project scenarios: a) Scenario 2, b) Scenario 3.

baseline scenario (current scenario), several key behavioural parameters for users and vehicles were established, namely: perception and reaction times, Aggressiveness level, Guidance acceptance level, vehicle dimensions, maximum acceleration/deceleration, maximum desired speed, etc. Simulations were conducted for each scenario, including the baseline scenario considering the evening peak hour (17:00–18:00). As for the car-following model, in AIMSUN the Gipps' formula [48] is implemented [49,50]. This formula allows the calculation of the maximum speed to which a vehicle (n) belongs to a platoon of vehicles can accelerate during the interval of time (t, $t + T$):

$$V_a(n, t+Tr) = V(n,t) + 2.5a(n)Tr\left(1 - \frac{V(n,t)}{V*(n)}\right)\sqrt{0.025 + \frac{V(n,t)}{V*(n)}} \tag{27}$$

where:

- V(n, t) is the speed of the vehicle n at the time instant t;
- V*(n) is the desired speed of the vehicle (n) in its current location;
- a(n) is the maximum acceleration for the vehicle n in its current location;
- T_r is the drivers' reaction time.

The maximum speed that the same vehicle (n) can reach during the same time interval (t, $t + T$), according to its own characteristics and the limitations imposed by the presence of the lead vehicle ($n - 1$), is:

$$V_b(n, t+Tr) = d(n)Tr + \sqrt{d(n)^2 Tr^2 - d(n)\left[2\{x(n-1,t) - s(n-1) - x(n,t)\} - V(n,t)Tr - \frac{V(n-1,t)^2}{d'(n-1)}\right]} \tag{28}$$

where:

Table 2
Summary of the estimated construction cost of each project scenario.

	Item	Length [m] / Number	Cost [€]
Scenario 1	Roundabout 1 ($R = 21.5$ m)	1	500,000
	Roundabout 2 ($R = 56.0$ m)	1	1000,000
	Demolitions		5000,000
	Tunnel (under the roundabout)	300	7500,000
	Viaduct (overpass the roundabout)	240	3600,000
	Roads	400	400,000
	Pavement for roads, tunnels and bridges		423,000
	Pavement for roundabouts		587,025
	Scenario 1 - Total construction cost [€]		**19,010,025**
Scenario 2	Roundabout 1 ($R = 21.5$ m)	1	500,000
	Roundabout 2 ($R = 56.0$ m)	1	1000,000
	Demolitions		5000,000
	Tunnel (under the roundabout)	300	7500,000
	Viaduct (overpass the roundabout)	240	3600,000
	Roads	400	400,000
	Pavement for roads, tunnels and bridges		463,500
	Pavement for roundabouts		587,025
	Bypass lane	90	90,000
	Scenario 2 - Total construction cost [€]		**19,140,525**
Scenario 3	Roundabout 1 ($R = 21.5$ m)	1	500,000
	Roundabout 2 ($R = 56.0$ m)	1	1000,000
	Demolitions		5000,000
	Tunnel (under the roundabout)	300	7500,000
	Viaduct (overpass the roundabout)	240	3600,000
	Roads	450	450,000
	Pavement for roads, tunnels and bridges		594,750
	Pavement for roundabouts		587,025
	Bypass lane	90	90,000
	Widening of the San Giorgio Bridge	92	1104,000
	Scenario 3 - Total construction cost [€]		**20,425,775**

- d(n) is the maximum deceleration desired by vehicle n;
- x(n, t) is the position (abscissa) of the vehicle n at time t;
- $x(n-1, t)$ is the position (abscissa) of the preceding vehicle $(n-1)$ at time t;
- $s(n-1)$ is the length of the vehicle $(n-1)$;
- $d'(n-1)$ is an estimation of the vehicle $(n-1)$ desired deceleration.

The speed of the vehicle (n) in the time interval $(t, t+T_r)$ is evaluated as the minimum of the values calculated with expressions (27) and (28):

$$V(n, t+Tr) = \min\{V_a(n,t+Tr), V_b(n,t+Tr)\} \quad (29)$$

The position of the vehicle n is calculated as follows:

$$x(n, t+Tr) = x(n, t) + V(n,t+Tr)Tr \quad (30)$$

The behaviour of vehicles AIMSUN is simulated also with additional models, including the lane-changing model, look-ahead model, microscopic gap-acceptance model, etc.

The traffic simulator must be able to emulate the traffic variables, such as speed, queue length, delays, etc., whose values must be very close to the measured values in real operation conditions. It is, therefore, essential to calibrate the traffic model. The calibration of the traffic model in AIMSUN needs adjusting the drivers and vehicle parameters until the output data agree closely with the observed data from the real world. Therefore, the probability (P_r) of the difference between the real the simulated values of a given traffic variable must be less than a pre-fixed acceptable difference, within a given level of significance [49, 51-52]:

$$P_r(|\text{real system} - \text{symulated system}| \leq \delta) > \alpha \quad (31)$$

In which δ is the tolerable difference threshold indicates how close the microscopic model is to reality and α represents the significance level.

As objective functions, different measures of goodness of fit can be adopted: root mean square error (RMSE), root mean squared normalized error (RMSNE), mean error (ME), mean normalized error (MNE), GEH index [49-50]. The letter was applied in this study. GEH (Geoffrey E. Havers) index is calculated with the relation [49-50]:

$$GEH_i = \sqrt{\frac{2(x_i - y_i)^2}{x_i + y_i}} \quad (32)$$

In which x_i and y_i are the *i*th simulated and observed values of the traffic variable under consideration (e.g. flow, density, queue, etc.).

It then estimates an aggregated index using the following algorithm [49]:

For $i = m$ (number of counting stations)
If $GEH_i \leq 5$, then set $GEH_i = 1$
Otherwise set $GEH_i = 0$
End if;
End for;

Let:

$$GEH = \frac{1}{m}\sum_{1=1}^{m} GEH_i \quad (33)$$

If $GEH \geq 85$ % then accept the model, otherwise reject the model
Endif.

The simulation model can be accepted when the deviation between simulated and measured values of the traffic variable under consideration satisfies Eq. (33).

In this study, vehicle acceleration was the primary parameter for

Table 3
Origin-destination matrix for the project scenarios (cf. Figs. 4 and 5) – Time interval 17:00–18:00.

O/D	1	2	3	4	5	6	7	8	9	10	11	12	13
1	0	0	499	0	420	0	0	167	0	0	22	54	0
2	0	0	0	0	0	0	438	0	0	0	0	0	0
3	0	0	0	0	10	0	250	50	0	0	170	40	0
4	0	0	190	0	20	0	150	50	0	0	50	10	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	145	0	152	0	0	0	0	0	365	98	0
8	0	0	150	0	0	0	102	0	0	0	66	139	0
9	0	0	0	0	0	0	0	0	0	1594	0	0	0
10	0	0	0	0	0	0	0	0	2049	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	10	0	8	0	300	5	0	0	300	0	0
13	0	0	0	0	0	0	30	0	0	0	27	0	0

calibrating the AIMSUN model [46,47]. Specifically, after setting a maximum acceleration range of 3.50–4.20 m/s^2 and a normal deceleration range of 3.70–4.90 m/s^2 (deduced during real-world measures by a proper instrumented vehicles) based on the entry conditions of the current scenario (baseline scenario), a GEH value of approximately 88 % was achieved when comparing the simulated and observed queues (x_i and y_i) estimated by a drone. Consequently, the traffic model was deemed acceptable and applied to the three project scenarios.

In particular, the baseline Scenario (Fig. 3) was simulated in the AIMSUN environment, taking into consideration 24-time intervals of 5 min, for a total of 2 h (the first O/D matrix is those of Table 1; th second one is not included here for the sake of synthesis). As shown in Table 4, the GEH index, calculated considering the deviation between simulated queue (x_i) and observed queue (y_i) values allows us to accept the microscopic traffic model since it satisfies the limits defined above (cf. Eq. 33). As a matter of fact, it results: GEH $= (22.00+23.00+20.00+19.00)/(4 \times 24)*100 = 88\ \% >$ the minimum acceptable value GEH $= 85$ %.

3.3. Safety assessment

The vehicle trajectories obtained from the traffic microsimulation can be used as input for the safety assessment based on Surrogate Safety Measures (SSMs). In this case, the SSAM (Surrogate Safety Assessment Module) software was utilized to identify potential conflict points. SSAM is a software created by Siemens Energy and Automation, Inc. in cooperation with the Federal Highway Administration in 2008 [53]. The integration of AIMSUN Next and the SSAM offers a robust framework for evaluating the safety performance of various new roundabout design scenarios in the absence of real accident data [53-55]. By generating accurate trajectory data (file .trj), AIMSUN Next sets the stage for SSAM to conduct a comprehensive safety analysis. The entire workflow of the proposed procedure, including that of the SSAM, is displayed in Fig. 6.

SSAM processes the vehicles' trajectories, routes and speed change to identify and categorize traffic conflicts, leveraging surrogate safety measures such as Time-to-Collision (TTC) and Post-Encroachment Time (PET) to predict potential collision points without relying solely on historical crash data.

In this study, the threshold TTC for recording conflicts is set equal to 1.5 s, as suggested in previous research on the application of SSAM to urban road intersections [53,56]. According to the angle θ between a couple of vehicles, traffic conflicts are categorized into three types [54] (Fig. 7): rear-end conflict ($\theta < 30°$), lane change conflict ($30° \leq \theta \leq 85°$) and crossing conflict ($85° < \theta \leq 180°$).

This methodological synergy between AIMSUN Next and SSAM enables a proactive safety assessment, highlighting the efficacy of proposed designs in mitigating conflicts and enhancing overall traffic safety.

4. Results and discussion

The analysis of the three project scenarios under the traffic demand represented by the O/D Matri of Table 3 reveals distinct performance metrics in terms of vehicle density, space mean speed, number of conflict points, delays, and construction costs as summarized in Table 5. Scenario 1, with a density of 38.32 veh/km and a space mean speed of 22.66 km/h, experienced a high number of conflict points at 4378, along with a delay of 91.56 s/veh, all within a project cost of approximately €19.01 million (Table 2). When a right-turn bypass lane was introduced in Scenario 2, the density decreased to 32.53 veh/km, although the speed was slightly reduced to 20.46 km/h. This modification led to a marginal reduction in conflict points (4327) but resulted in an increased delay of 108.5 s/veh, with a slight increase in cost to €19.14 million (Table 2). Scenario 3, involving a modification in the carriageway of the bridge San Giorgio, exhibited significant improvements: a density of 36.38 veh/km, the highest speed of 28.82 km/h, and the fewest conflict points at 3675, all correlating with the lowest delay of 57.55 s/veh. However, these benefits come at the highest cost of approximately € 20.43 million (Table 2). This analysis suggests that Scenario 3, despite its higher upfront cost, offers the best overall improvement in terms of level of service and safety. Moreover, the surrogate safety analysis clarifies that Scenario 3 gives lower crossing, rear-end, lane change and total conflict points values, as shown in Fig. 8.

To run the two optimization models, weights from 0.1 to 1.0 (with an increment of 0.1) were assigned to each criterion and compute a weighted score (cf. Sect. 2) for each scenario by multiplying the

Table 4
GEH_i index, calculated with the measured (y_i) and estimated (x_i) queue values (24 intervals of time of 5 min) for four roundabout entries (cf. Fig. 3).

Simulation n.	Entry 1				Entry 3				Entry 4				Entry 6			
	y_i	x_i	GEX_i	Set value of GEX_i	y_i	x_i	GEX_i	Set value of GEX_i	y_i	x_i	GEX_i	Set value of GEX_i	y_i	x_i	GEX_i	Set value of GEX_i
1	8	6	0.48	1	11	4	2.49	1	6	6	0.00	1	14	9	1.64	1
2	8	5	1.00	1	11	9	0.82	1	6	10	1.41	1	8	12	1.10	1
3	6	5	0.43	1	8	9	0.42	1	11	16	1.51	1	13	10	0.71	1
4	6	3	1.70	1	10	4	1.93	1	5	6	0.65	1	13	9	1.26	1
5	5	6	0.75	1	8	11	1.11	1	8	14	1.98	1	17	14	0.82	1
6	9	9	0.08	1	13	7	2.12	1	8	8	0.18	1	15	10	1.45	1
7	8	6	0.48	1	11	11	0.12	1	6	14	2.53	1	31	5	6.07	1
8	8	4	1.58	1	13	7	2.12	1	12	8	1.26	1	15	10	1.45	1
9	11	6	1.47	1	15	11	1.16	1	9	18	2.45	1	24	12	2.82	1
10	11	10	0.16	1	23	18	1.16	1	15	18	0.74	1	22	19	0.82	1
11	14	10	1.02	1	19	18	0.33	1	12	18	1.55	1	21	22	0.24	1
12	14	9	1.42	1	25	9	3.88	1	14	30	3.54	1	24	12	2.82	1
13	14	10	1.02	1	23	18	1.16	1	12	18	1.55	1	24	27	0.67	1
14	15	9	1.81	1	21	15	1.29	1	17	26	2.06	1	21	19	0.52	1
15	18	13	1.41	1	25	22	0.56	1	17	36	3.81	1	27	31	0.75	1
16	18	15	0.74	1	30	31	0.07	1	20	30	2.11	1	28	5	5.63	0
17	14	17	0.76	1	23	29	1.14	1	27	38	1.93	1	22	24	0.29	1
18	19	14	1.23	1	29	33	0.81	1	20	32	2.46	1	31	36	0.85	1
19	23	20	0.54	1	36	35	0.15	1	29	4	6.08	0	41	12	5.60	0
20	21	18	0.80	1	42	31	1.83	1	20	30	2.11	1	41	44	0.55	1
21	27	20	1.44	1	36	35	0.15	1	33	62	4.21	1	32	31	0.29	1
22	20	16	0.94	1	46	51	0.72	1	44	10	6.48	0	38	8	6.26	0
23	14	41	5.15	0	46	77	4.01	1	54	20	5.59	0	39	7	6.76	0
24	13	39	5.10	0	67	15	7.99	0	53	12	7.13	0	57	12	7.73	0
TOTAL				**22**				**23**				**20**				**19**

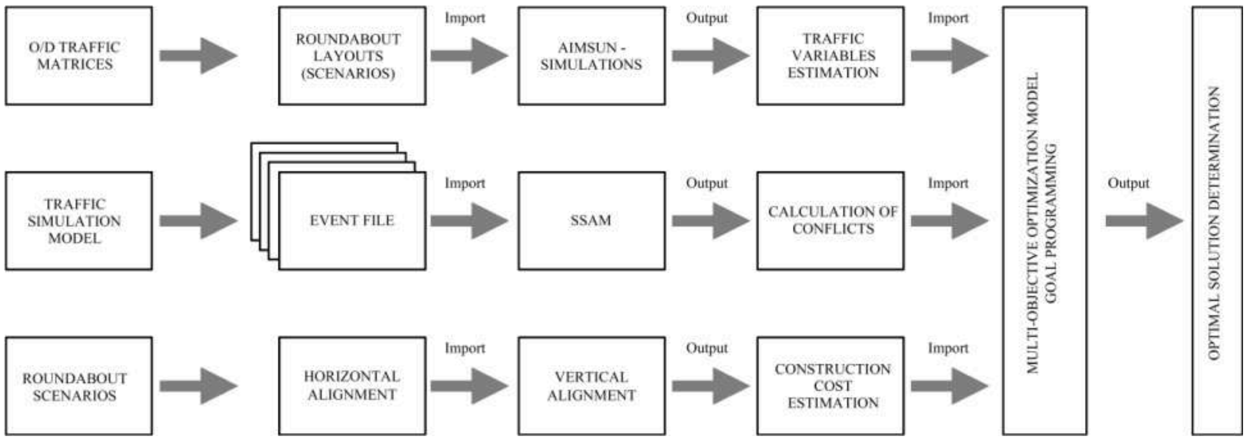


Fig. 6. Workflow of the proposed Multi-Objective Method.

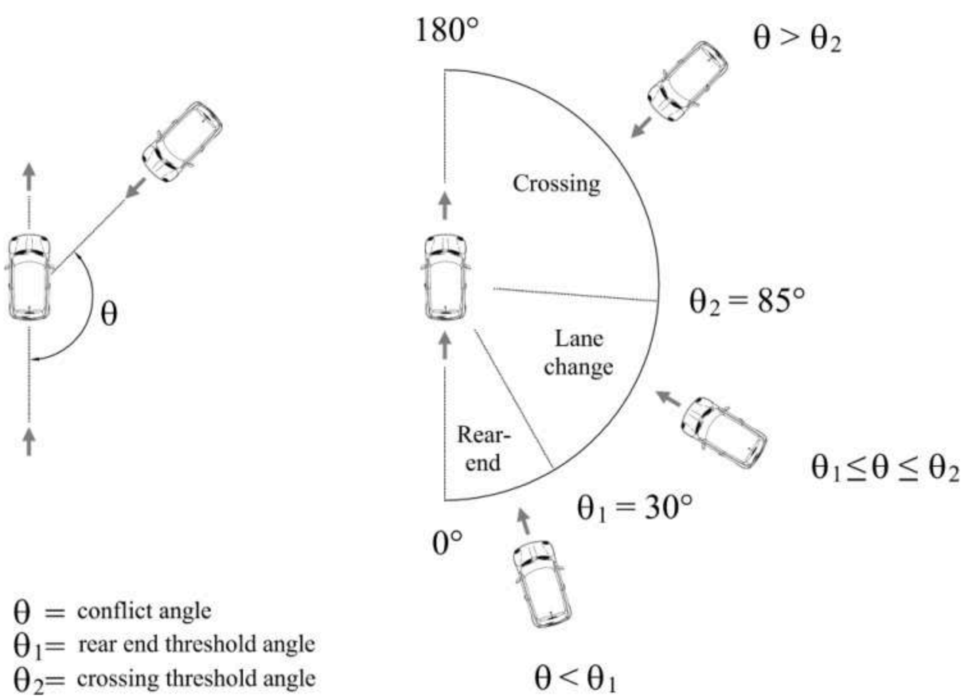


Fig. 7. Classification of conflict types in SSAM [40].

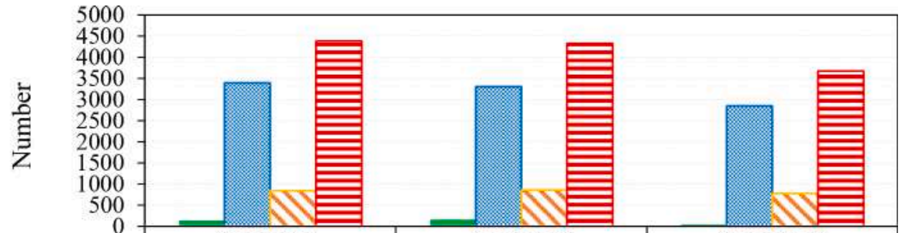
Table 5
Main simulation results.

Scenarios	Vehicle density [veh/km]	Space mean speed [km/h]	Total number of conflict points	Delay [s/veh]	construction cost [€]
Scenario 1	38.32	22.66	4378	91.56	19,010,025
Scenario 2	32.53	20.46	4327	108.5	19,140,525
Scenario 3	36.38	28.82	3675	57.55	20,425,775

normalized variables by these weights. This method accounts for different importance (weights) of each parameter (e.g., speed, delay) in evaluating roundabout scenarios.

The bar chart in Fig. 9 delineates the percentage of roundabouts being identified as the optimal solution across the three project scenarios (i.e. Scenario 1, Scenario 2 and Scenario 3). The data reveals a pronounced preference for Scenario 3, with a percentage exceeding 90 %, indicating their substantial effectiveness and suitability in this context. In contrast, Scenario 2 records a significantly lower percentage, approximately 10 %, suggesting a less frequent but still notable optimality of roundabouts. Scenario 1 shows minimal frequency, underscoring the specificity of context in determining the optimal traffic solution. Therefore, these findings particularly highlight the distinct advantages of only one layout (i.e. Scenario 3) for this case study.

The pair plot in Fig. 10 offers an in-depth visualization of the relationships between various weight parameters (e.g., speed weight, delay weight, density weight, conflict weight, and cost weight) and their combined impact on the winning score across different project scenarios (Scenario 1, Scenario 2, Scenario 3). The point distribution reveals a clear pattern, showing that the winning score generally increases with higher speed weight and conflict weight, supporting previously observed positive correlations. The scatter plots display distinct clusters for each project scenario, with Scenario 3 (blue points) consistently achieving higher winning scores. The diagonal density plots highlight the distribution of each variable, with cost weight showing a negative



	Scenario 1	Scenario 2	Scenario 3
Crossing	142	164	51
Rear-end	3390	3302	2851
Lane change	846	861	773
Total	4378	4327	3675

Fig. 8. Number of crossings, rear-end, lane change and total conflict points estimated for the project scenarios.

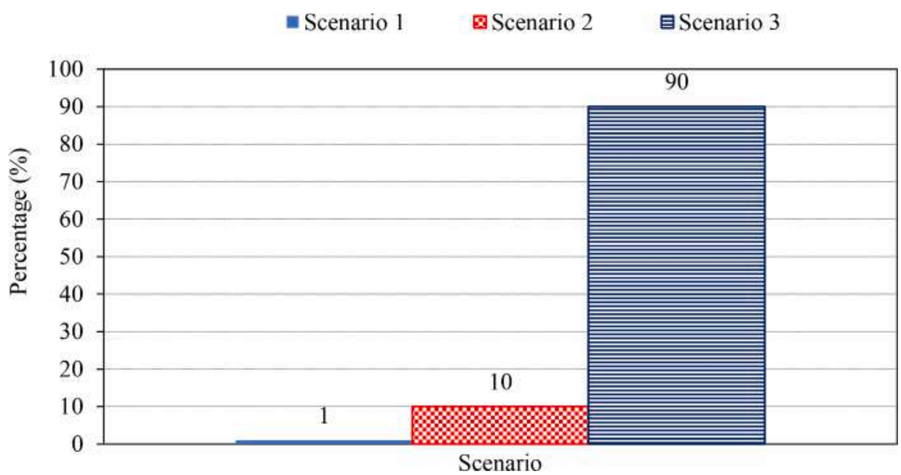


Fig. 9. Percentage of selecting each Scenario for multi-objective model.

skew, underscoring its inverse relationship with the winning score. Additionally, the plots illustrate minimal variance in density weight across scenarios, indicating a lesser impact on performance outcomes. These visual insights underscore the importance of prioritizing weights such as speed and conflict points, particularly in Scenario 3, to optimize winning outcomes.

The bar chart in Fig. 11, obtained from the GP, illustrates the percentage distribution of roundabouts being selected as the optimal solution across three project scenarios. Scenario 3 remains the dominant context in this second model, with roundabouts being identified as optimal in over 80 % of the cases. Scenario 2 shows a modest percentage of around 15 %, indicating a notable, though less frequent, optimality and the Project Scenario maintains a minimal percentage. These results further emphasize the significant advantages of project Scenario 3 for this case study, corroborating the distinct context-dependent efficacy observed in the initial model.

The pair plot in Fig. 12 illustrates the interplay between various optimization weights (i.e., speed weight, delay weight, density weight, conflict weight, and cost weight) and their impact on the Winning Score across different project scenarios. Each scatter plot within the matrix compares two weights, revealing distinct clusters for each project scenario, with Scenario 3 (blue points) consistently achieving higher winning scores. Density plots along the diagonal offer insights into the distribution of each weight, highlighting notable trends, such as the oscillatory pattern in speed weight and conflict weight, which correlates positively with the winning score. Additionally, the plots indicate minimal variance in density weight and cost weight across scenarios, suggesting their lesser impact on performance outcomes. These visualizations emphasize the importance of prioritizing certain weights, particularly those correlated to speed and conflict point variables, to optimize project outcomes effectively.

To identify the benefits linked to different configurations and dimensions of large roundabouts in terms of capacity, safety and environmental sustainability, it is possible to effectively adopt the proposed method, both in scientific and technical fields, in analogy with what was found in previous research on other roundabout types [57,58].

Finally, a sensitivity analysis was applied using three normalization methods, Z-Score, Min-Max, and Robust, to evaluate the roundabout optimization criteria. The results (Fig. 13) have highlighted very specific patterning in how each method affects scoring dynamics under varying weights for each criterion. The Z-Score method has followed the approach of adjusting data to be based on the mean and standard deviation; in this case, it has shown a constant distribution in scores for all scenarios and weights. There is clear uniform sensitivity that may hide the subtlety of differences between several roundabout designs. Min-Max normalization presents escalating score variability, and its sensitivity is more marked on extreme data values. This allows clear delineation of relative impacts between maximum and minimum values, especially highlighting the performance difference for scenarios with very contrasting criteria values.

More so, Robust normalization, which scales the data by the median and interquartile range, is rather insensitive to outliers, though it produces a scoring pattern that remains consistent across various scenarios. One might argue that it is also adequate for situations with potential outliers or skewed distributions. This implies that a lower score corresponds to a higher weight for all criteria in the context of Density, Delay,

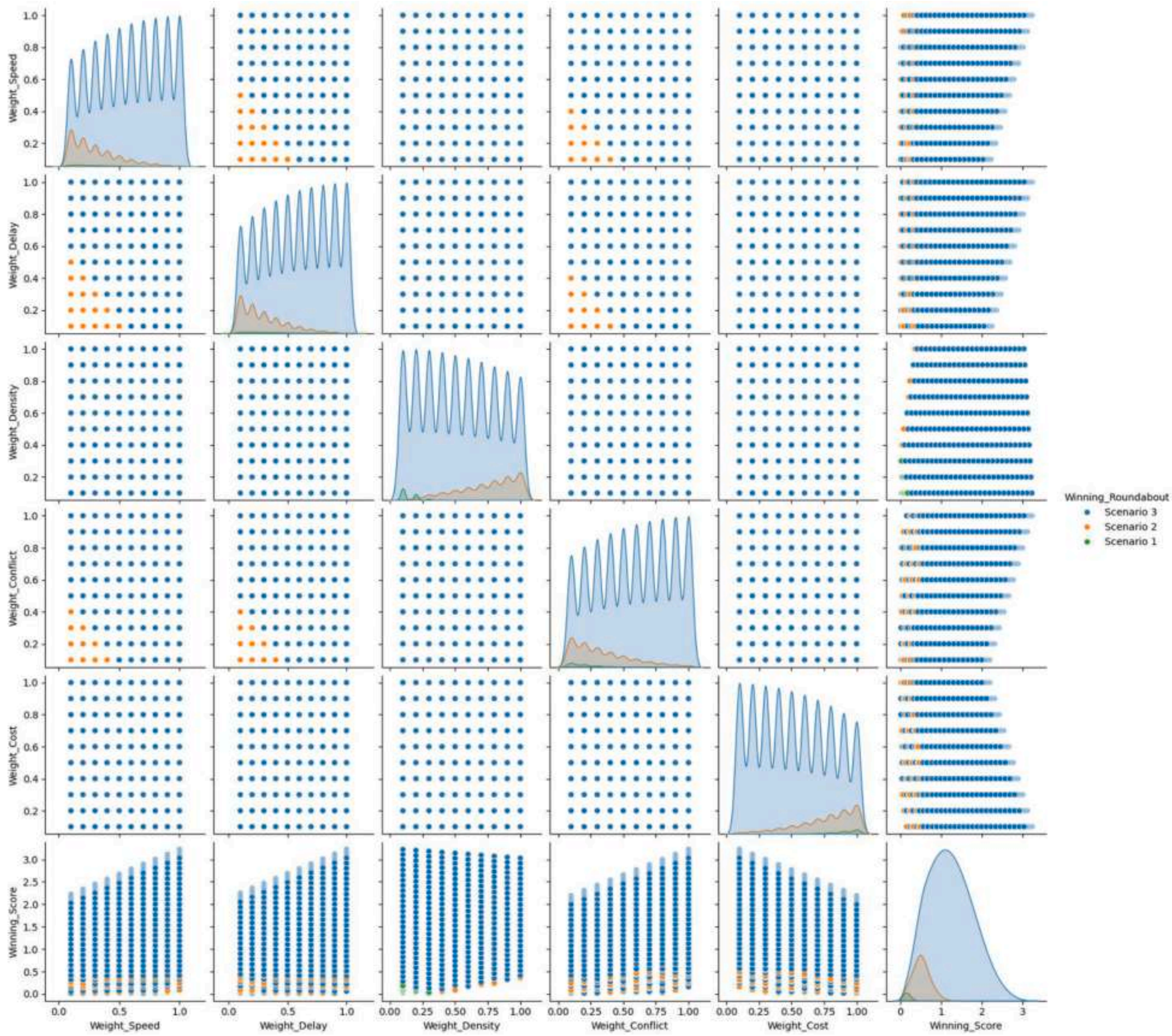


Fig. 10. Visualization of results for Multi-objective Model.

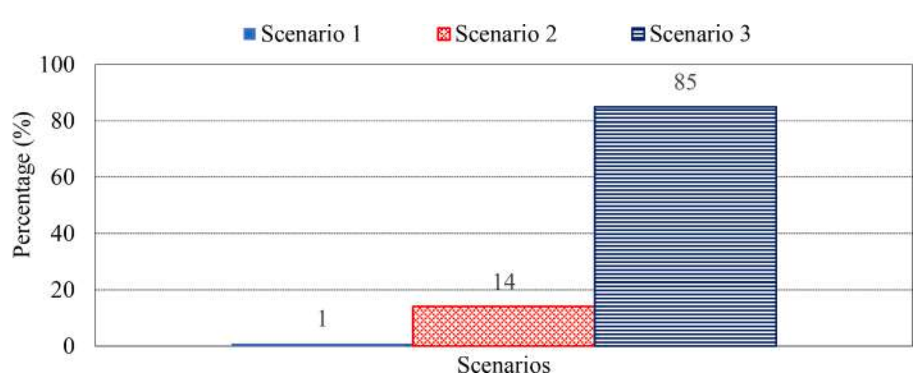


Fig. 11. Percentage of selecting each scenario for Goal Programming model.

Conflict Points, and Cost. As a result, these factors must be minimized in roundabout design to enhance overall performance and cost-effectiveness. The consistent patterns observed across different normalization methods may offer valuable insights into specific designs' inherent strengths and weaknesses, meriting further investigation or reconsideration. This extended evaluation supports more informed decision-making in urban planning and traffic management by incorporating the added value that normalization approaches provide in the interpretative and practical optimization of sensitivity analysis. Based on these findings, Z-Score normalization is recommended for its ability to facilitate informative and precise comparisons among scenarios, thereby ensuring a comprehensive evaluation of roundabout performance metrics.

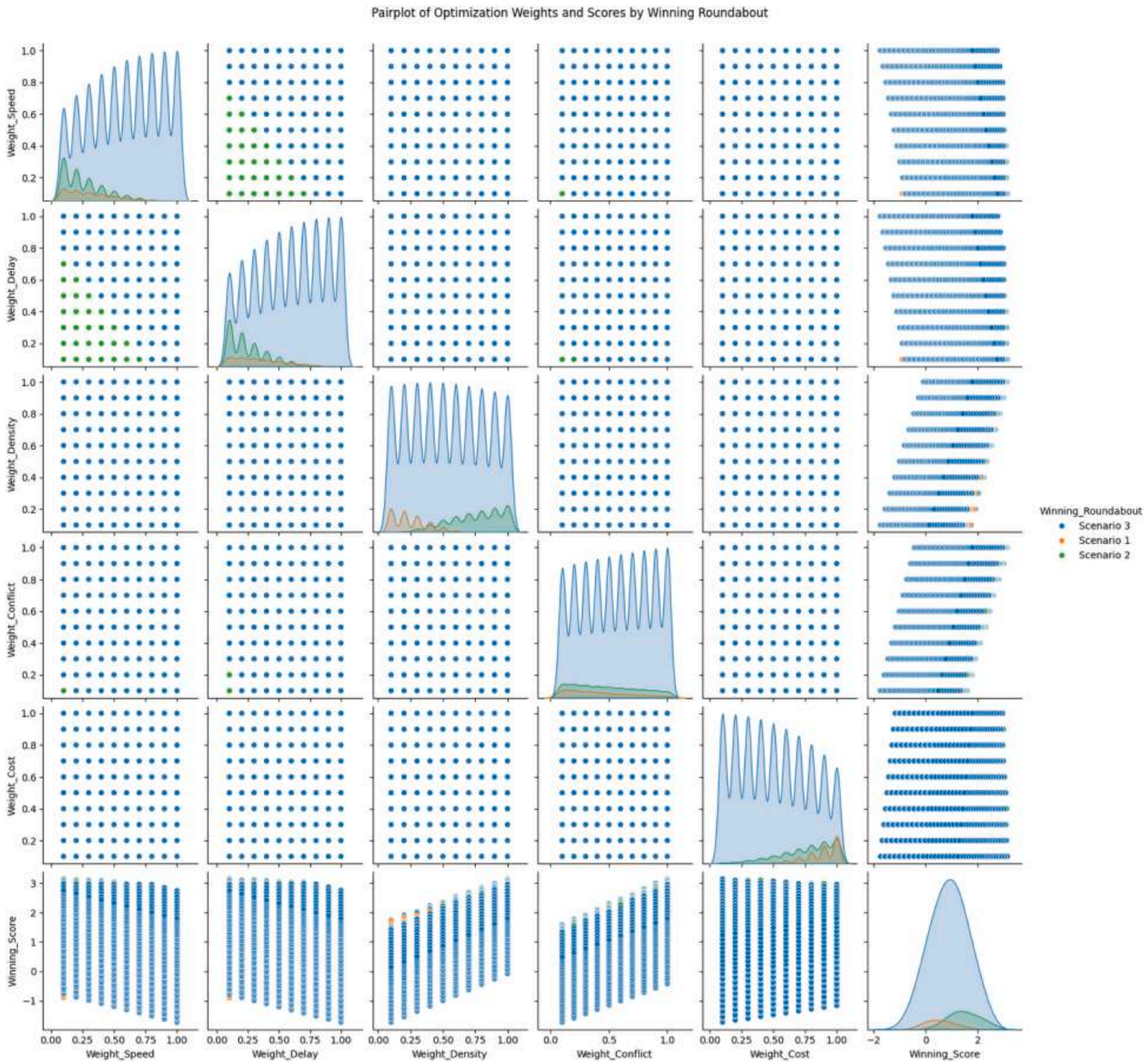


Fig. 12. Visualization of results for Goal programming Model.

5. Conclusions

The present research has demonstrated the efficacy of integrating traffic simulation-based and safety analysis with goal programming for optimizing roundabout design in complex urban road networks. By employing advanced microscopic traffic simulation tools like AIMSUN Next and Surrogate Safety Assessment Models (SSAMs), it is possible to assess multiple design scenarios and their impacts on speed capacity, delays (i.e. level of service) and safety. The proposed multi-objective optimization approach, which includes both robust and goal programming models, has effectively balanced conflicting criteria such as minimizing space vehicle density, delay, and construction cost and maximizing the space mean speed in the simulated road network.

5.1. Major findings and limitations of the study

The case study's results underscore the proposed methodology's potential to enhance large roundabout performance, particularly highlighting the superiority of a scenario in improving the Measure of Effectiveness (MOE) and safety metrics.

This paper proposes two different optimization techniques, namely Multi-Objective Optimization (MOO) and Goal Programming (GP), used to solve problems encountered in the large roundabout design. Basically, MOO is useful where the aim is to determine the best possible design configurations by optimizing and attributing importance to several criteria that were considered and GP's focus is on getting as close as possible to the predetermined set of targets. MOO enables the balance of the different design variables while GP enables the satisfaction of target parameters such as safety and efficiency within the designs.

A comparison of the two models adopted in this research (i.e. a robust multi-objective optimization model and a goal programming model) reveals distinct strengths and applications. The robust multi-objective optimization model excels in providing a systematic approach for evaluating various simulations of a roundabout by considering normalized criteria and weighted sums. This model is particularly effective for identifying the best design configurations under different weight scenarios, offering flexibility in prioritizing different traffic parameters. On the other hand, the goal programming model focuses on minimizing deviations from predefined targets for multiple goals, providing a more tailored solution that aligns closely

Fig. 13. Results of the sensitivity analysis.

with specific safety and efficiency targets. This model is advantageous for scenarios where specific goals, such as maximizing speed or minimizing delays, are of paramount importance. This research provides valuable insights for traffic and transportation engineers, emphasizing the importance of a holistic, data-driven approach to large roundabout design, even if the proposed procedure can be applied to other intersection types and road network configurations.

However, this research has some limitations since only one large roundabout in an urban context was analyzed.

5.2. Research perspectives

Future research may focus on refining the models by incorporating real-time data from connected and autonomous vehicles to further enhance predictive accuracy and optimization. Additionally, exploring the integration of environmental impact assessments and pedestrian safety measures could provide a more comprehensive evaluation of roundabout designs. Ultimately, this study contributes to the advancement of sustainable urban traffic management strategies, paving the way for safer and more efficient large roundabouts that can adapt to the evolving demands of modern transportation networks in sustainable cities."

CRediT authorship contribution statement

Marco Guerrieri: Writing – original draft, Supervision, Methodology, Investigation, Conceptualization. **Masoud Khanmohamadi:** Writing – original draft, Software, Methodology, Formal analysis, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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