

Article

Evaluating Roundabout Performance Using Agent-Based Simulation: A Case Study

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Abstract

Compared to conventional signalised intersections, roundabouts are increasingly recognised for their ability to improve traffic safety and operational efficiency. However, accurately modelling their complex traffic dynamics remains challenging, particularly in multilane configurations characterised by lane-changing manoeuvres and gap-acceptance interactions. This study presents a behaviour-driven microscopic simulation framework based on agent-based modelling (ABM) for evaluating roundabout performance under varying geometric and traffic demand conditions. In the proposed framework, each vehicle is represented as an autonomous agent capable of route selection, yielding, lane-changing, and speed adaptation according to predefined behavioural rules. This enables a detailed representation of local traffic interactions and operational conflicts that are not fully captured by traditional aggregate traffic models. The simulation environment is used to analyse idealised one-, two-, and three-lane roundabout configurations and to assess the operational impact of targeted geometric modifications. The proposed methodology is further validated using real-world traffic data collected from the Braşov Central Roundabout, Romania. Simulation results demonstrate that the ABM framework can realistically reproduce traffic throughput, average speed, number of stops, and travel time under high traffic demand conditions. Furthermore, the introduction of a channelised right-turn lane resulted in measurable operational improvements, including increased average speed and reduced delay. The findings highlight the applicability of agent-based simulation as a decision-support tool for roundabout design, traffic management, and infrastructure optimisation, contributing to safer and more efficient urban mobility systems.



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1. Introduction

Roundabout intersections are increasingly adopted worldwide as an effective solution for improving traffic efficiency and reducing severe vehicle collision conflicts compared to conventional signalised intersections, although their safety performance may vary depending on road users and geometric design [1]. Their geometric configuration promotes continuous vehicle movement, eliminates signal delay and reduces the number of conflict points, leading to documented safety and operational benefits in urban traffic networks.

Recent studies confirm that roundabouts can significantly improve traffic performance under both moderate and high demand conditions, provided that their geometric design and operational characteristics are properly optimised [2–4].

Despite these advantages, the operational behaviour of multilane roundabouts remains complex due to frequent lane-changing manoeuvres, gap-acceptance decisions, and interactions between circulating and entering vehicles. These dynamics are strongly influenced by driver behaviour and geometric layout, making accurate modelling a persistent challenge for traffic engineers and urban planners. Traditional macroscopic and mesoscopic traffic models often rely on aggregated flow assumptions, which limit their ability to capture localised interactions and behavioural heterogeneity, particularly in high-density multilane roundabouts [5,6].

Earlier studies on roundabout safety and operational performance provide an important foundation for the present work. Crash-based investigations have shown that roundabout safety depends strongly on geometric configuration, user behaviour and conflict type [7–9]. Design-oriented references further emphasise the role of entry geometry, circulatory width, deflection and gap-acceptance behaviour in determining roundabout capacity and safety [3,10,11]. From an operational perspective, capacity analyses and microsimulation studies have demonstrated that entry flow, circulating flow, merging behaviour, and weaving interactions are critical factors in roundabout performance, particularly in multilane layouts [12–14].

Recent studies have also investigated unconventional roundabout configurations, such as turbo roundabouts and spiral lane designs, which aim to reduce weaving conflicts and improve operational efficiency under high traffic demand conditions [15,16].

In recent years, agent-based modelling (ABM) has emerged as a powerful microscopic simulation approach capable of representing individual vehicle behaviour and interaction dynamics in complex traffic environments. In ABM frameworks, each vehicle is modelled as an autonomous agent governed by behavioural rules such as gap acceptance, lane-changing, yielding, and speed adaptation. This allows for a more realistic representation of traffic flow compared to traditional models, especially in environments characterised by non-linear interactions and adaptive decision-making [17,18]. Recent reviews of agent-based modelling in urban transportation have highlighted its ability to represent individual decision-making, heterogeneous interactions and emergent traffic patterns, while also emphasising the importance of calibration and validation using empirical traffic data [19].

However, despite the growing interest in ABM-based traffic simulation, its application to real-world multilane roundabouts remains relatively limited, particularly with respect to empirical validation using observed traffic data. Many existing studies focus on theoretical scenarios or simplified junction layouts, with limited consideration of complex urban roundabouts and actual geometric constraints [2,20,21]. Moreover, few studies explicitly compare agent-based simulation outcomes with field-measured traffic performance indicators, such as entry capacity, travel time and number of stops, under real operating conditions.

Agent-based modelling has also been widely used in transport and urban systems beyond roundabout analysis. Previous studies have shown that agent technology can support traffic and transportation modelling by representing individual decision-making, interaction rules and emergent system-level behaviour [22,23]. Microscopic simulation approaches, including cellular automata and agent-based formulations, have been applied to reproduce local traffic interactions and dynamic network behaviour [24,25]. ABM has also been used in broader urban-system applications where individual decisions and spatial interactions generate complex collective patterns [26]. In addition, real-world urban traffic studies highlight the importance of empirical data and calibration when analysing operational conditions and vehicle behaviour in urban environments [12,27].

Recent advances in traffic modelling have increasingly incorporated machine learning, artificial neural networks and deep learning methods, particularly for traffic-flow prediction, adaptive traffic control and pattern recognition in large-scale traffic datasets [28,29]. Such approaches are highly effective when extensive historical or real-time data are available for training predictive models. However, the objective of the present study is not short-term traffic prediction, but the interpretable simulation of vehicle interactions and geometric effects in multilane roundabouts. For this reason, a rule-based agent-based modelling framework was adopted, as it enables explicit representation of gap acceptance, yielding, lane-changing, and conflict-resolution mechanisms while preserving transparency in the evaluation of geometric design alternatives.

In the specific context of roundabout simulation, Vieira et al. [20] applied agent-based microsimulation to assess roundabout performance using different variables and performance indicators, while Korp [21] investigated agent behaviour modelling in roundabout traffic, highlighting the importance of driver decision-making, gap acceptance and interaction rules. These studies confirm the relevance of agent-level modelling for roundabout analysis but also show that further work is needed on empirical validation using real-world traffic data and site-specific calibration.

Against this background, the present study proposes an agent-based simulation framework for evaluating roundabout performance under varying geometric configurations and traffic demand levels, with a particular emphasis on multilane roundabouts. The model explicitly captures individual vehicle interactions, lane-changing behaviour, and gap-acceptance processes, enabling a detailed assessment of operational performance metrics, including vehicle throughput, average speed, number of stops and time spent in the system. In addition to analysing idealised one-, two- and three-lane roundabout designs, the study incorporates a real-world case study of the Braşov Central Roundabout (Romania) to validate the simulation results against empirical traffic observations.

The main contributions of this study are threefold. First, it provides a systematic comparison between theoretical capacity calculations and agent-based simulation results for different roundabout configurations. Second, it validates the ABM approach using real-world traffic data collected from a high-volume multilane roundabout, addressing a key gap identified in recent literature. Third, it demonstrates how targeted geometric modifications—such as the introduction of a channelised right-turn lane—can significantly improve operational performance, highlighting the practical value of ABM as a decision-support tool for infrastructure design and traffic management.

The remainder of the paper is structured as follows. Section 2 describes the agent-based modelling methodology and simulation setup, including behavioural assumptions and geometric configurations. Section 3 presents the simulation results for idealised roundabout layouts, while Section 4 discusses the findings in relation to existing literature and evaluates the real-world case study, while Section 5 concludes the paper by summarising the main contributions and outlining directions for future research.

1.1. Objectives

The primary objective of this study is to evaluate the operational performance of roundabout intersections using an agent-based modelling (ABM) approach. By employing a microscopic, behaviour-driven simulation framework, the study aims to capture individual vehicle interactions and assess how traffic demand and geometric design influence overall roundabout efficiency.

The specific objectives of this research are as follows:

- A. To analyse the impact of traffic volume and roundabout geometry on key operational performance indicators, including entry capacity, average speed, number of stops, and time spent in the system.
- B. To compare theoretical roundabout capacity models with agent-based simulation results in order to assess their applicability under realistic traffic conditions.
- C. To identify the primary factors influencing lane utilisation and traffic efficiency in multilane roundabouts, with particular attention to lane-changing behaviour and exit conflicts.
- D. To examine the influence of gap-acceptance behaviour and rule-based driver decision-making on roundabout throughput, assuming average driver characteristics.
- E. To validate the agent-based simulation results using empirical traffic data from a real-world multilane roundabout case study, namely the Braşov Central Roundabout.

1.2. Agent Based Modeling Simulation

Agent-based modelling (ABM) is employed in this study as a microscopic simulation approach for analysing traffic flow at roundabout intersections. In contrast to aggregate traffic models, ABM represents each vehicle as an autonomous agent whose motion and decisions are governed by a predefined set of behavioural rules and interaction mechanisms. This enables a detailed representation of local traffic dynamics arising from vehicle–vehicle and vehicle–infrastructure interactions.

In the proposed simulation framework, each vehicle agent is individually initialised with physical and behavioural attributes, including desired speed, acceleration and deceleration limits, entry and exit paths, and gap-acceptance thresholds. Agents navigate the roundabout environment by continuously evaluating surrounding traffic conditions and applying rule-based decision-making processes related to yielding, lane-changing, speed adaptation, and exit selection. The model assumes average driver behaviour, focusing on compliance with traffic rules and excluding extreme aggressive or non-compliant actions.

The ABM approach offers several advantages for modelling roundabout traffic operations. First, it allows for a realistic representation of driver behaviour by explicitly modelling gap acceptance and lane-changing manoeuvres, which are critical processes in multilane roundabouts. Second, the framework is scalable and capable of handling high traffic volumes while preserving detailed agent-level interactions. Third, the modelling structure is flexible, allowing geometric configurations and traffic demand levels to be modified without altering the underlying behavioural logic.

To ensure transparency and reproducibility, the overall simulation workflow is illustrated using a structured flowchart (Figure 1). The process begins with the initialisation of the simulation environment and vehicle agents, followed by route assignment and entry into the roundabout network. During each simulation step, agents assess local traffic conditions, apply behavioural rules, update their state variables (position, speed, lane), and interact dynamically with other agents. The simulation concludes with the extraction of key performance indicators, including entry capacity, average speed, number of stops, and time spent in the system. This agent-based simulation framework provides the methodological foundation for evaluating both idealised roundabout designs and a real-world multilane roundabout case study, enabling a consistent and behaviourally realistic assessment of operational performance under varying traffic conditions.

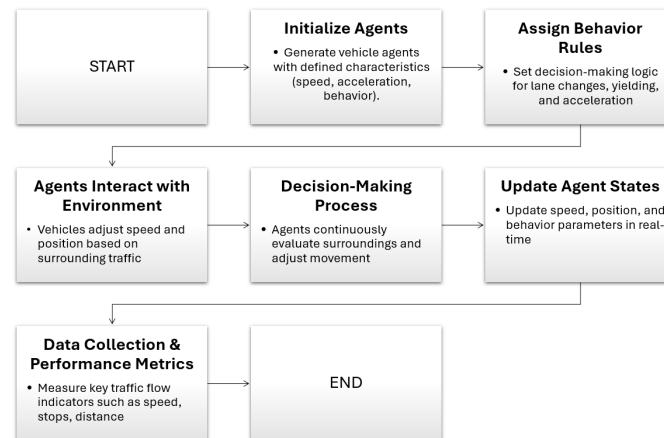


Figure 1. Simulation workflow.

This diagram illustrates the operational workflow of the agent-based simulation model employed to evaluate roundabout traffic performance. The process commences with the initialisation of agents, where each vehicle is assigned specific attributes such as speed, acceleration and behavioural characteristics. Behavioural rules are subsequently applied to govern agent decisions, including lane-changing, gap acceptance, yielding, and acceleration. Agents interact with their environment and continuously assess surrounding traffic conditions through a dynamic decision-making process. These interactions lead to real-time updates of agent states (e.g., position and speed). The simulation concludes with the collection of performance metrics such as travel time, average speed, number of stops, and overall traffic flow efficiency. This structured methodology enables a high-fidelity representation of individual driver behaviour and its impact on junction performance.

2. Methods Used

The proposed methodology is based on microscopic agent-based traffic simulation implemented within the AnyLogic Road Traffic Library environment. The framework combines geometric modelling, behavioural rule implementation and dynamic traffic interaction analysis to reproduce multilane roundabout operations under varying traffic demand conditions.

Each vehicle is represented as an autonomous agent capable of performing route selection, speed adaptation, gap acceptance, yielding and lane-changing manoeuvres according to predefined behavioural rules. The simulation environment enables continuous interaction between agents and surrounding traffic conditions, allowing the emergence of realistic traffic patterns and congestion phenomena.

The methodological workflow includes geometric configuration modelling, traffic demand definition, behavioural calibration, simulation execution and extraction of operational performance indicators. This structure enables direct comparison between analytical calculations, idealised simulation scenarios and real-world traffic observations.

Key components of the ABM simulation are as follows:

Pathfinding algorithms: determining optimal vehicle routes based on entry and exit points.

Decision-making mechanisms: modelling driver behavior, including acceleration, lane-changing, and yielding.

Traffic Interaction modelling: simulating vehicle interactions at roundabout entry and circulatory lanes.

By incorporating these algorithms, the simulation accurately represents complex traffic dynamics and allows for an in-depth evaluation of various roundabout configurations,

vehicle flow scenarios, and safety considerations. The methodology also enables comparative analysis between simulated and real-world traffic data, ensuring the robustness of the findings.

2.1. Simulation Architecture

The simulation architecture consists of three main functional components:

Pathfinding and route assignment:

Each vehicle agent is assigned an entry and exit point upon generation. Route selection is determined prior to entering the roundabout and remains fixed throughout the simulation, reflecting typical driver route commitment in urban roundabout navigation.

Behavioural decision-making module:

The behavioral rules implemented in the simulation are defined as deterministic rule-based mechanisms. At roundabout entries, vehicles yield to circulating traffic and enter only when an acceptable gap is available. Gap acceptance is calibrated using the critical-gap and follow-up-time values adopted in the analytical capacity calculation. Lane-changing manoeuvres are performed only when the target lane provides sufficient longitudinal spacing and when the manoeuvres does not conflict with circulating or exiting vehicles. Acceleration and deceleration behaviour is constrained by the maximum values defined in Table 1, while conflict resolution is governed by priority rules: circulating vehicles and vehicles already occupying the target lane retain priority, whereas entering or lane-changing vehicles decelerate or stop when the available gap is insufficient.

Table 1. Car parameters used in the simulation.

	Parameter	Unit
Vehicle length	5	meter
Initial speed	60	Km/h
Preferred speed	80	Km/h
Maximum acceleration	2.2	m/s ²
Maximum deceleration	4.35	m/s ²

Driver behaviour is modelled using rule-based decision logic governing acceleration, deceleration, gap acceptance, lane-changing and yielding at roundabout entries and exits. Agents continuously evaluate surrounding traffic conditions and adjust their speed and position accordingly. The behavioural parameters are calibrated to represent average driver behaviour, without explicitly modelling aggressive or non-compliant driving patterns.

Traffic interaction and conflict modelling:

Vehicle interactions are explicitly simulated at both entry points and within the circulatory lanes. Conflicts arising from merging, weaving and exit manoeuvres are resolved based on gap-acceptance thresholds and right-of-way rules. This allows the model to capture internal roundabout conflicts that significantly influence operational performance in multilane configurations.

2.2. Simulation Execution and Output Metrics

The simulation is executed over a fixed time horizon sufficient to reach stable traffic conditions. During the simulation, vehicle trajectories, speeds, lane changes and stop events are recorded at the agent level. From these data, key performance indicators are extracted, including entry capacity, average speed, number of stops per vehicle and time spent in the system. The methodological framework supports direct comparison between simulation outputs and real-world traffic observations. By replicating the geometric layout and traffic

demand of an existing multilane roundabout, the model enables empirical validation of the ABM approach and assessment of its suitability for practical traffic engineering applications.

2.3. Ideal Intersection Design

The simple roundabout consists of one central lane and one entry lane. This is the basic intersection used in most cases where the traffic volumes are not high enough to require extra lanes. The idealised one-, two-, and three-lane roundabout layouts used in this study are presented in Figure 2, Figure 3 and Figure 4, respectively. The dimensions used are also presented. For this study, the central island has a radius of 20 m, which is the standard value for most intersections [3,11].

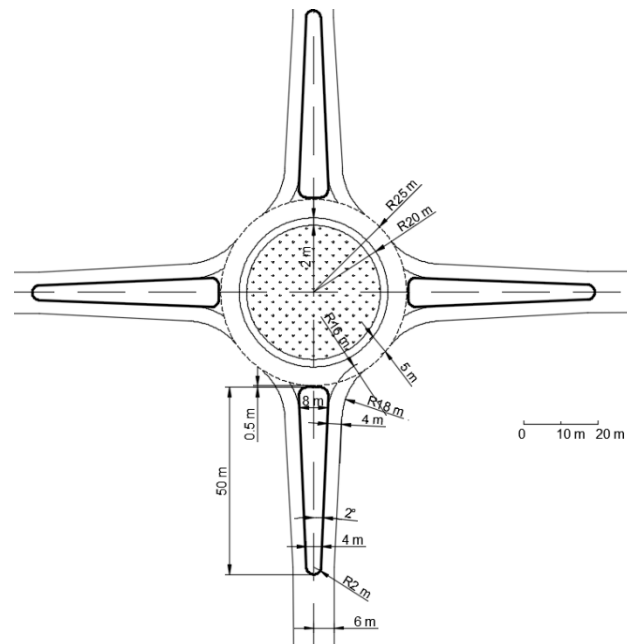


Figure 2. One lane on the inner circle roundabout intersection.

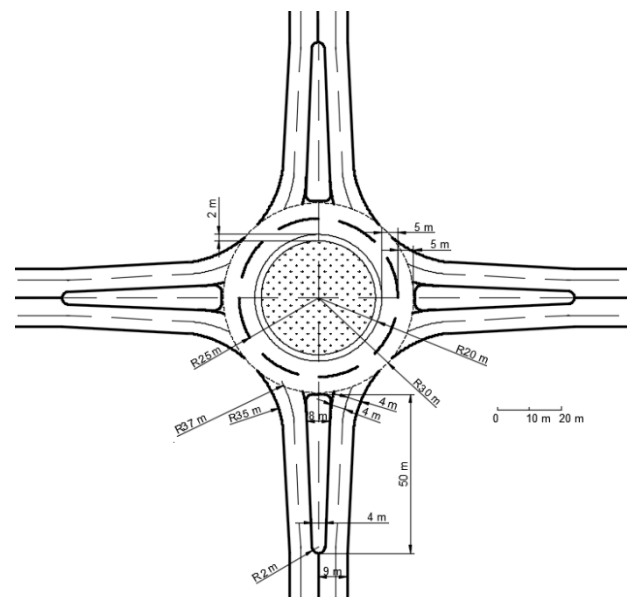


Figure 3. Two lanes on the inner circle roundabout intersection.

2.4. Traffic Parameters

To conduct the agent-based simulations, a set of traffic and vehicle parameters was defined to represent typical urban passenger car behaviour. These parameters include vehicle length, initial speed at entry, preferred speed, and maximum acceleration and deceleration rates. The selected values, summarised in Table 1, are consistent with commonly reported characteristics of passenger vehicles operating in urban traffic conditions.

For simplification purposes, the simulated traffic stream consists exclusively of passenger cars. This assumption was adopted to isolate the influence of roundabout geometry and traffic demand on operational performance and to ensure consistency between theoretical capacity calculations and simulation outputs. The real-world case study intersection is located in a central urban area, where heavy goods vehicles are limited; nevertheless, the presence of buses, motorcycles and bicycles is acknowledged. The exclusion of heterogeneous vehicle types therefore represents a modelling limitation and is addressed as a direction for future research.

All vehicle agents are initialised with identical physical parameters and follow the same behavioural rules, representing average driver behaviour. No stochastic variability in vehicle performance parameters is introduced, allowing for a controlled comparison between different geometric configurations and traffic volumes. Traffic demand is specified in vehicles per hour (veh/h), which represents a direct count of vehicles entering the roundabout. Passenger Car Units (PCU) are not used in this study, as only a single vehicle class is considered.

This parameterisation ensures a transparent and controlled simulation environment, suitable for evaluating relative performance differences between roundabout configurations rather than absolute capacity under mixed traffic conditions.

2.5. Preliminary Calculations

To establish a reference framework for evaluating the agent-based simulation results, preliminary analytical calculations were performed to estimate the theoretical entry capacity of each roundabout configuration. These calculations are based on established gap-acceptance theory and are commonly used in roundabout capacity analysis [14].

For the single-lane roundabout, the entry capacity is calculated using Equation (1), which accounts for critical gap time, follow-up time and conflicting traffic volume within the circulatory lane. The resulting capacity represents an idealised maximum value under steady-state conditions and uniform driver behaviour.

$$C = \frac{M_c \cdot e^{-\frac{M_c \cdot t_g}{3600}}}{1 - e^{-\frac{M_c \cdot t_f}{3600}}} \quad (1)$$

For multilane roundabouts, Equation (2) is employed to extend the single-lane formulation by incorporating the number of circulatory and entry lanes, as well as the minimum time gap between successive vehicles. This analytical approach provides an upper-bound estimate of capacity and does not explicitly account for internal conflicts arising from lane-changing manoeuvres within the roundabout.

$$C_{rb} = 3600 \cdot \left(1 - \frac{t_{\min} \cdot M_c}{n_{cl} \cdot 3600}\right)^{n_{cl}} \cdot \frac{n_{el}}{t_f} \cdot e^{-\frac{M_c}{3600} \left(t_g - \frac{t_f}{2} - t_{\min}\right)} \quad (2)$$

The conflicting traffic volume is determined using Equation (3), which aggregates the flows associated with return, left-turn and right-turn movements. For consistency across configurations, a constant conflicting flow of 1000 veh/h is assumed. Capacity calculations

were performed for one-, two- and three-lane roundabout designs, and the resulting values are reported in Table 2.

$$M_c = M_{return} + M_{left} + M_{right} \quad (3)$$

where M_{return} is the volume of vehicles that do a turn around manoeuvre in the roundabout, M_{left} is the traffic that turns left, and M_{right} is the conflicting traffic that turns right [veh/h]. For this study, the conflict traffic volume is considered 1000 veh/h. In Table 2, the calculations were carried out for a 1-lane, 2-lane and 3-lane roundabout capacity separately.

Table 2. Calculated roundabout capacity.

Type of Roundabout	No. of Circle Lanes	No. of Entry Lanes	Critical Time Gap [s]	Consecutive Time Gap [s]	Calculated Capacity [veh/h]
1-lane roundabout	1	1	4,4	3,1	510
2-lane roundabout	2	2	4,4	3,1	824
3-lane roundabout	3	3	4,4	3,1	1368

It should be emphasised that these analytical calculations serve solely as a baseline for comparison. Unlike the analytical capacity models, the agent-based simulation explicitly captures vehicle interactions, lane-changing behaviour and exit conflicts, which are particularly relevant in multilane roundabouts. Therefore, deviations between analytical and simulation-based capacity estimates are expected and are analysed in the subsequent sections.

2.6. Simulation Calibration and Execution

The agent-based simulations were implemented using the AnyLogic simulation environment under controlled and reproducible operating conditions. Each simulation scenario was executed over a total simulation interval of 3600 s, corresponding to one hour of simulated traffic operation. All simulations were initiated at $t = 0$ s and terminated automatically after the predefined simulation duration.

During the early stages of the simulation, traffic density gradually increased as vehicles entered the network. Stable circulation patterns and localised queue formation became observable after approximately 100 s of simulation time, indicating the transition from free-flow initialisation conditions to representative traffic operation. To minimise the influence of transient initialisation effects, the first 300 s of each simulation was treated as a warm-up period and excluded from the evaluation of operational performance indicators.

Calibration of the model was performed by adjusting traffic demand inputs and behavioural parameters, including gap-acceptance logic and lane-changing behaviour, until the simulated throughput values and operational indicators showed acceptable agreement with the measured traffic data collected at the Braşov Central Roundabout.

For consistency and comparability, identical simulation durations and behavioural parameter settings were applied to all one-, two- and three-lane roundabout scenarios. The modelling framework represents average driver behaviour using deterministic rule-based logic and therefore does not explicitly include stochastic variability in aggressiveness, reaction time or rule compliance. This simplification was intentionally adopted to isolate the influence of roundabout geometry and traffic demand on operational performance.

3. Traffic Flow Simulation

Simulations were performed using the agent-based modelling framework described in Section 2 to evaluate the operational performance of one-, two- and three-lane roundabout configurations. For each scenario, traffic demand, vehicle parameters and behavioural rules were kept constant to ensure comparability across designs.

The primary performance indicators analysed include entry capacity, average vehicle speed, number of stops per vehicle, and time spent in the system. These metrics were extracted directly from agent-level simulation data after the system reached steady-state conditions.

$$s_a = \frac{d_a}{t_s} \quad (4)$$

where d_a is the travelled distance of each agent [m] and t_s is the time in system for each agent [s]. The time in system is calculated as the difference between the simulation time t and the start time of each agent that enters the simulation t_a .

$$t_s = t - t_a \quad (5)$$

The two parameters t_a and d_a are obtained and calculated for each individual agent during the simulation. Running the simulation will show the maximum achieved capacity as well as the density, speed and number of stops. Figure 4 shows the results.

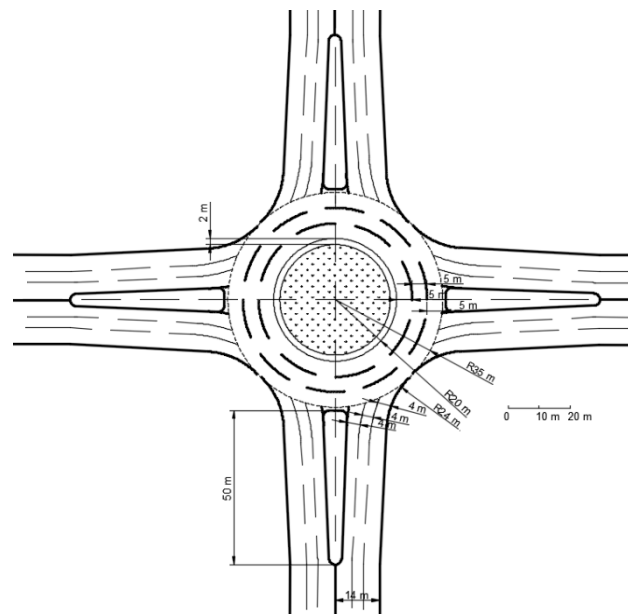


Figure 4. Three lanes on the inner circle roundabout intersection.

3.1. Simulation of the 1-Lane Roundabout

The simulation results for the single-lane roundabout configuration are presented in Figures 5 and 6. Under the specified traffic demand, the average entry capacity across all approaches was 502 veh/h, which is closely aligned with the analytically estimated capacity of 510 veh/h.

The capacity of each entry is presented in Figure 6. As we can see, the roundabout is balanced, having an average of 502 veh/h. This result is very similar to the calculated value.

The simulation yielded an average vehicle speed of 19 km/h, an average of 1.18 stops per vehicle and a mean travel time of approximately 59 s. The density map illustrates a uniform utilisation of the circulatory lane, with no pronounced congestion zones observed at any entry. The corresponding operational performance indicators are summarised in Figure 7.

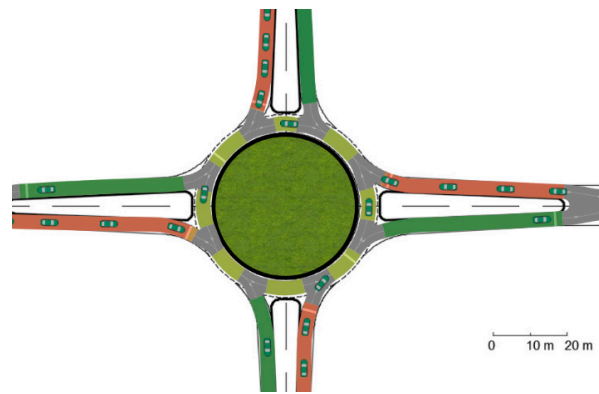


Figure 5. Simulation of the one-lane roundabout and AnyLogic density map. Colours represent local traffic speed over 50 m road sections, ranging from red, approximately 5 km/h or lower, to green, approximately 50 km/h or higher.

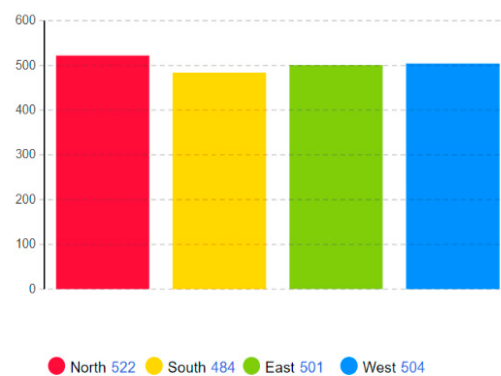


Figure 6. Capacity of each entry side of the roundabout.

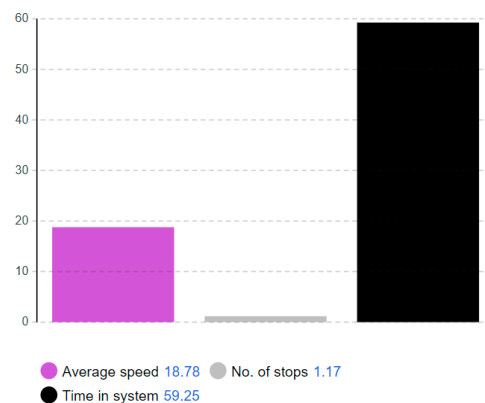


Figure 7. 1-lane roundabout performance.

3.2. Simulation of the 2-Lane Roundabout

The simulation of a 2-lane roundabout aims to analyse the impact of increased lane capacity on traffic flow efficiency and vehicle throughput. Compared to a 1-lane roundabout, this configuration allows for higher entry and circulatory volumes, potentially reducing congestion and improving overall performance. The simulated two-lane roundabout layout and density map are shown in Figure 8.

The capacity resulting from the simulation is shown for each entry in Figure 9. We can observe that the average capacity was 765 veh/h, similar to the calculated value of 824 veh/h. The difference comes from the delay that occurs when vehicles within the circle lanes want to leave the circle but have to give way to the other lane in the circle. In this case, the average speed was 29 km/h, the number of stops was 0.55 and the travel time was 54 s.

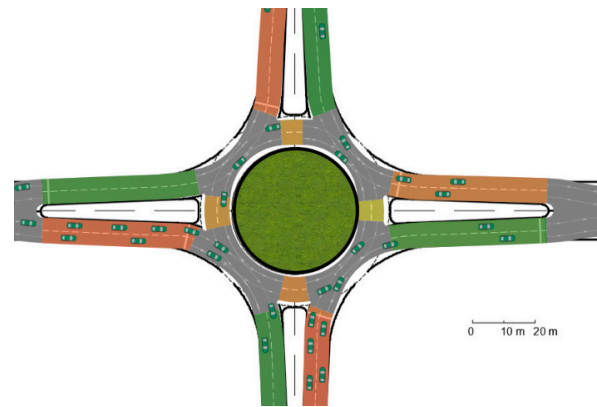


Figure 8. Simulation of the two-lane roundabout and AnyLogic density map. The colour scale represents local traffic speed over 50 m road sections, with red indicating very low speed/congested traffic conditions, approximately 5 km/h, and green indicating free-flow conditions, approximately 50 km/h.

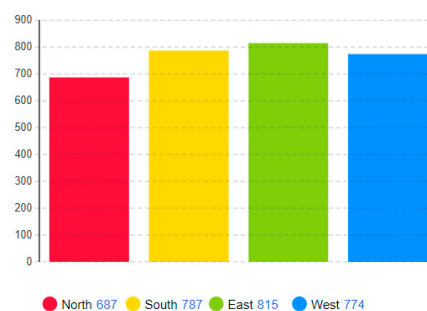


Figure 9. Capacity of each entry side of the roundabout for the 2-lane design.

The corresponding operational performance indicators are summarized in Figure 10.

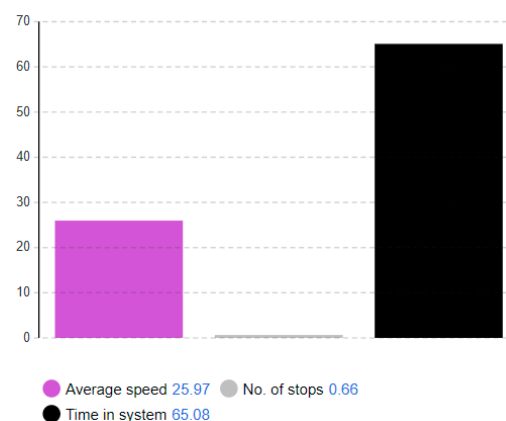


Figure 10. 2-lane roundabout performance.

3.3. Simulation of the 3-Lane Roundabout

The agent-based simulation of the three-lane roundabout configuration was conducted using the same traffic demand and behavioural parameters applied in the previous scenarios to ensure consistency and comparability. The geometric layout includes three circulatory lanes and three entry lanes on each approach. The simulated three-lane roundabout layout and density map are shown in Figure 11.

The simulated entry capacities for the three-lane roundabout are presented in Figure 12. The average entry capacity obtained from the simulation is 1242 veh/h, with individual approach values of 1240 veh/h (northbound), 1250 veh/h (southbound), 1234 veh/h (eastbound) and 1247 veh/h (westbound). These results indicate a relatively balanced utilisation of all approaches under the specified traffic demand.

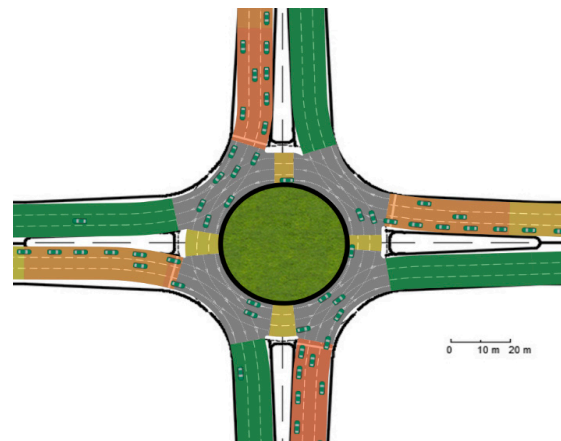


Figure 11. Simulation of the three-lane roundabout and AnyLogic density map. Colours represent local traffic speed over 50 m road sections, ranging from red, approximately 5 km/h or lower, to green, approximately 50 km/h or higher.

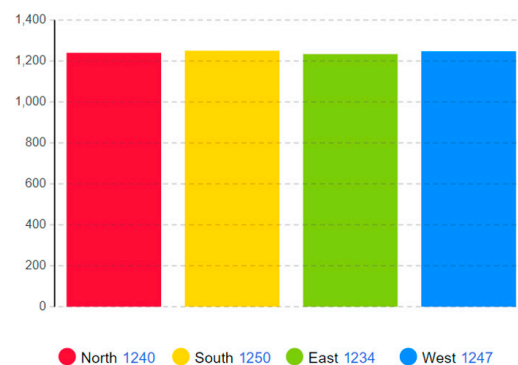


Figure 12. Capacity of each entry side of the roundabout for the 3-lane design.

Operational performance indicators for the three-lane configuration are shown in Figure 13. The simulation yielded an average vehicle speed of 34.92 km/h, a mean number of 0.64 stops per vehicle and an average time spent in the system of 84.24 s. The density map associated with this configuration, illustrated in Figure 11, indicates higher vehicle concentrations within the circulatory roadway compared to the one- and two-lane scenarios.

These results demonstrate that increasing the number of circulatory lanes leads to higher entry capacity and improved average speed, while also affecting the time vehicles spend within the roundabout system under high traffic demand conditions.

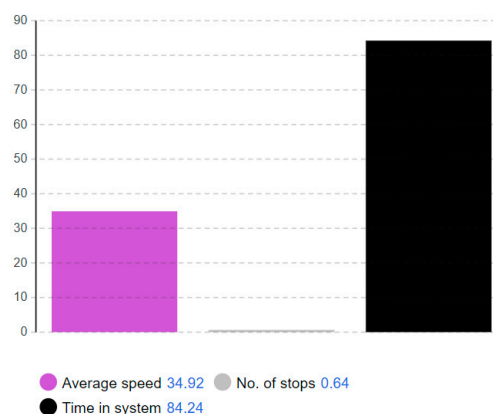


Figure 13. 3-lane roundabout performance.

4. Discussion

This section discusses the simulation results in relation to real-world traffic conditions and established roundabout performance principles. The discussion focuses on the ability of the agent-based modelling (ABM) framework to reproduce observed traffic behaviour at a complex multilane roundabout and to evaluate the operational impact of targeted geometric modifications.

4.1. Comparison with Real-World Situation

To validate the accuracy and practical applicability of the proposed agent-based modelling approach, simulation results were compared with empirical traffic data collected at the Braşov Central Roundabout. This intersection represents a high-demand urban roundabout with a three-lane circulatory roadway and three-lane entries on all four approaches, as illustrated in Figure 14. Owing to its geometry, traffic volume and operational complexity, the intersection provides a suitable case study for assessing the realism of microscopic traffic simulation.



Figure 14. Real-world case intersection of the 3-lane configuration.

Observed traffic volumes were recorded during peak-hour conditions and are summarised in Table 3, where entry flows are categorised by movement type (left turn, through and right turn). The total observed volumes range from 823 veh/h on the northbound approach to 1523 veh/h on the eastbound approach, indicating pronounced directional imbalance typical of urban traffic conditions.

Table 3. Measured values for the Brasov roundabout.

Entry	Left Turn [veh/h]	Through [veh/h]	Right Turn [veh/h]	Total Volume [veh/h]
Northbound	338	426	59	823
Southbound	389	646	216	1251
Westbound	367	430	77	874
Eastbound	401	585	537	1523

To reproduce the real-world configuration, the intersection geometry and entry demand were implemented in the ABM environment, as shown in Figure 15, which illustrates the simulated layout and lane usage patterns. The resulting simulated entry capacities are presented in Figure 16. The model produced entry volumes of 670 veh/h (northbound), 1170 veh/h (southbound), 1154 veh/h (eastbound) and 818 veh/h (westbound). While minor discrepancies are observed—particularly for the eastbound approach—the simulation captures the relative distribution of traffic demand across approaches and reproduces realistic throughput levels under high traffic load.



Figure 15. Simulation of the selected real-world intersection and AnyLogic density map. The satellite image is used as the geometric background, while the coloured road sections represent local traffic speed, ranging from red, approximately 5 km/h or lower, to green, approximately 50 km/h or higher.

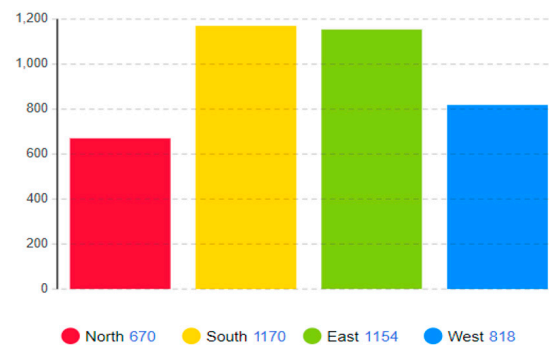


Figure 16. Capacity of each entry side of the roundabout for the real-world example.

The results of the agent-based simulation model, configured to replicate the traffic conditions of the Braşov Central Roundabout, are presented in Figure 16. The chart compares the simulated vehicle throughput for each entry approach, enabling a direct comparison with the real-world traffic volumes reported in Table 3.

Table 4 compares the measured and simulated entry flows and reports the corresponding percentage errors.

Table 4. Comparison between measured and simulated entry flows.

Entry	Measured [veh/h]	Simulated [veh/h]	Error [%]
Northbound	823	670	18.6
Southbound	1251	1170	6.5
Eastbound	1523	1154	24.2
Westbound	874	818	6.4

The average absolute percentage error between measured and simulated entry flows was approximately 13.9%, indicating acceptable agreement between the agent-based model and the observed traffic conditions for a microscopic traffic simulation framework.

In addition to the percentage error values, supplementary validation indicators were calculated. The mean absolute error (MAE) was 164.75 veh/h, the root mean square error (RMSE) was 205.71 veh/h, and the coefficient of determination between measured and simulated entry flows was $R^2 = 0.84$. These values indicate that the model reproduces the overall distribution of observed traffic flows with reasonable accuracy for a microscopic traffic simulation framework. The validation results should be interpreted as calibration

indicators for a deterministic ABM model rather than as formal statistical proof of universal predictive accuracy.

Operational performance indicators extracted from the simulation are shown in Figure 17, including average speed, number of stops per vehicle and time spent in the system. The results indicate an average speed of 31.59 km/h, approximately 1.22 stops per vehicle and a mean system time of 85.13 s. These values are consistent with the expected behaviour of a multilane roundabout operating near capacity, where internal conflicts and weaving manoeuvres contribute to increased delay despite multiple circulatory lanes.

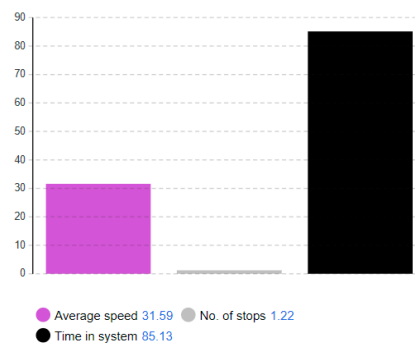


Figure 17. Operational performance of the real-world roundabout.

4.2. Impact of Geometric Refinement

Field observations revealed that the eastbound approach of the Braşov Central Roundabout includes a channelised right-turn movement, which reduces interaction with circulating traffic. To improve geometric fidelity and assess the operational effect of this feature, the simulation model was refined by adding a dedicated right-turn slip lane on the eastbound approach, as shown in Figure 18.



Figure 18. The addition of a right-turning vehicle lane. The red arrow indicates the added slip lane (bypass lane) for right-turning vehicles.

Following this modification, the simulation was rerun using identical traffic demand conditions. The updated entry capacities are presented in Figure 19, showing increased throughput for multiple approaches: 729 veh/h (northbound), 1177 veh/h (southbound), 1167 veh/h (eastbound) and 867 veh/h (westbound). The most notable improvement occurs on the eastbound approach, where isolating right-turning vehicles reduces conflicts at the yield line and within the circulatory roadway. The increase observed on the

westbound approach suggests that reducing localised conflicts can also improve overall circulatory flow.

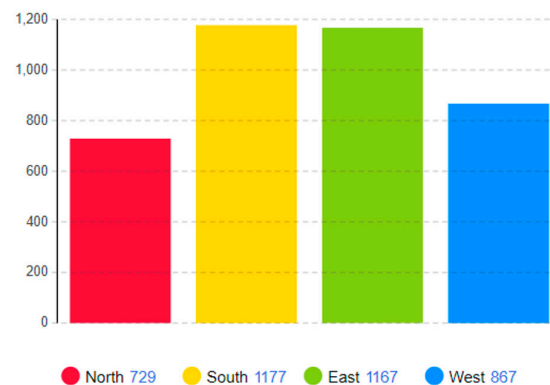


Figure 19. Capacity of each entry side of the roundabout for the real-world example, with a right lane.

The effect of the geometric refinement on operational performance is further illustrated in Figure 20. After introducing the channelised right-turn lane, the average speed increased to 34.34 km/h, the number of stops per vehicle decreased to 1.06, and the average time spent in the system was reduced to 74.71 s. These results demonstrate that even limited geometric modifications can yield measurable improvements in both efficiency and traffic continuity in high-volume multilane roundabouts.

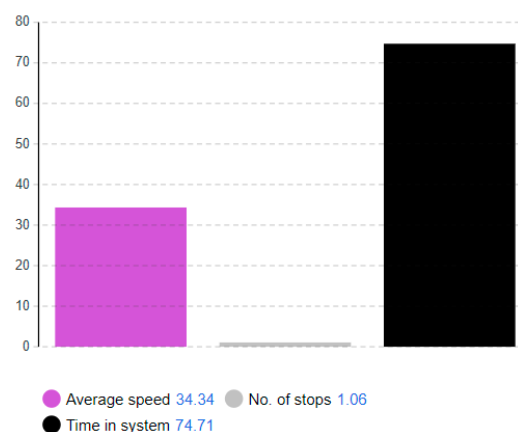


Figure 20. Operational performance of the real-world roundabout with a right lane.

4.3. Interpretation of Multilane Roundabout Behaviour

Across all simulations, the average number of stops per vehicle remained close to one, with an average travel time of approximately 59 s for the idealised three-lane roundabout configuration. However, the real-world case exhibited longer system times, reflecting the increased interaction complexity inherent to actual traffic conditions. In multilane roundabouts, vehicles exiting from inner lanes frequently interact with vehicles in outer lanes continuing through the intersection, leading to additional yielding events and localised delays.

The comparison between analytical capacity estimates and simulation results further highlights the limitations of traditional gap-acceptance models when applied to complex multilane roundabouts. While theoretical calculations provide upper-bound capacity values, the ABM simulation consistently produces lower but more realistic capacities by explicitly accounting for lane-changing behaviour and exit conflicts. For example, the idealised three-lane configuration yielded a simulated capacity of 1242 veh/h, while the real-world case study exhibited observed and simulated entry volumes ranging from approximately 1170 to 1523 veh/h, depending on approach and geometry.

Overall, the results confirm that agent-based modelling is well suited for capturing the interaction-driven dynamics of multilane roundabouts and for evaluating the operational effects of geometric design features under real traffic demand conditions.

The largest discrepancy between measured and simulated traffic volumes was observed on the eastbound approach. This deviation is likely associated with the increased complexity of traffic interactions generated by the high proportion of right-turn and merging manoeuvres on this entry. In addition, the deterministic behavioural assumptions used in the model may not fully capture aggressive gap acceptance and local driving patterns observed under congested urban traffic conditions. Despite this discrepancy, the simulation reproduced the overall traffic distribution and operational trends with acceptable accuracy for a microscopic traffic simulation framework.

This deviation also suggests that the eastbound approach is more sensitive to local behavioural variability than the other approaches. In real traffic, drivers may accept shorter gaps, use lanes more aggressively, or perform right-turn manoeuvres with different acceleration patterns than those represented by the deterministic average-driver model. Therefore, the larger eastbound error does not necessarily indicate a geometric modelling failure but rather highlights the importance of incorporating stochastic behavioural heterogeneity in future model extensions.

4.4. Limitations

Although the proposed agent-based modelling framework successfully reproduces the operational behaviour of multilane roundabouts under observed traffic demand conditions, several limitations should be acknowledged.

The simulation assumes a homogeneous traffic stream composed exclusively of passenger vehicles. Consequently, the effects of heavy vehicles, public transport, motorcycles, cyclists and pedestrians were not explicitly represented. These traffic participants may significantly influence gap-acceptance behaviour, lane utilisation and entry capacity under real urban traffic conditions.

In addition, all vehicle agents were assigned identical behavioural parameters representing average driver behaviour. The model therefore does not explicitly account for stochastic variability in aggressiveness, reaction time, driver compliance or risk-taking behaviour. While this simplification improves consistency and comparability between scenarios, it may reduce the realism of traffic interactions under highly dynamic or unpredictable operating conditions.

Behavioural heterogeneity could influence the obtained results by modifying accepted gaps, lane-changing frequency, queue discharge rates and the probability of localized conflicts. In future implementations, driver variability could be represented by assigning probabilistic distributions to key behavioural parameters, such as desired speed, reaction time, critical gap, acceleration, deceleration and lane-changing aggressiveness. Similarly, mixed traffic could be incorporated by defining separate agent classes for passenger cars, buses, motorcycles, cyclists, and pedestrians, each with specific physical dimensions, acceleration profiles, desired speeds, and yielding behaviour.

The model was calibrated using traffic observations collected from a single urban roundabout located in Braşov, Romania. As a result, the behavioural patterns and traffic distributions represented in the simulation may differ from those observed in other cities, countries or road environments. Variations in driving culture, infrastructure design and traffic regulations may influence the transferability of the proposed modelling framework.

Furthermore, the present study focuses on deterministic microscopic traffic simulation and does not incorporate adaptive or data-driven learning techniques. Consequently, rare

or anomalous traffic situations, such as incidents, atypical driver behaviour or sudden demand fluctuations, are not explicitly modelled.

From a robustness perspective, the present framework evaluates expected peak-hour traffic conditions and does not explicitly include out-of-distribution scenarios such as incidents, temporary lane blockages, abnormal driver behaviour, or sudden changes in demand. Although recent data-driven studies in other engineering fields have explored out-of-distribution augmentation and domain-generalisation strategies for improving robustness under unseen conditions, the present work remains a deterministic microscopic traffic simulation study. Nevertheless, similar concepts could inspire future traffic-simulation extensions, for example by generating synthetic anomalous traffic scenarios, testing the model under unseen demand patterns, and calibrating behavioural parameters across multiple urban contexts.

Despite these limitations, the proposed framework provides a robust basis for evaluating multilane roundabout performance and analysing the operational impact of geometric modifications under controlled traffic demand conditions. Future research should focus on integrating heterogeneous traffic compositions, stochastic behavioural models and broader multi-site validation to improve realism and generalisability.

5. Conclusions

This study investigated the operational performance of roundabout intersections using an agent-based modelling (ABM) approach, with a particular focus on multilane configurations and validation against real-world traffic data.

The results demonstrate that agent-based simulation can effectively reproduce key traffic performance indicators, including entry capacity, average speed, number of stops and time spent in the system. For idealised roundabout layouts, increasing the number of circulatory lanes leads to higher throughput and reduced stopping frequency; however, this improvement is accompanied by increased internal interactions and, in some cases, longer travel times due to lane-changing and exit conflicts.

Validation using empirical data from the Braşov Central Roundabout confirmed the suitability of the proposed modelling framework for complex urban environments. The simulated entry capacities and operational performance indicators closely matched observed traffic behaviour, indicating that the ABM approach can realistically capture interaction-driven dynamics in high-volume multilane roundabouts.

Furthermore, the introduction of a channelised right-turn lane in the simulation demonstrated measurable improvements in traffic performance, including increased average speed, reduced number of stops and shorter system travel times. These findings highlight the effectiveness of targeted geometric optimisation and illustrate the value of agent-based modelling as a decision-support tool for evaluating design interventions prior to implementation.

Although the model was calibrated using data from the Braşov Central Roundabout, the proposed framework can be adapted to other roundabout layouts and traffic demand scenarios by recalibrating geometric, behavioural and traffic-flow parameters.

Overall, the study confirms that agent-based modelling provides a robust and flexible framework for analysing and improving the performance of complex roundabout intersections. Future research should extend the model to include heterogeneous vehicle types, stochastic driver behaviour, and interactions with vulnerable road users, as well as broader validation across multiple sites and traffic conditions.

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Abbreviations

The following abbreviations are used in this manuscript:

ABM	agent-based modelling
PCU	Passenger Car Unit
C	single-lane roundabout capacity, veh/h
M_c	conflict traffic volume, veh/h
t_g	critical time gap, s
t_f	follow-up time / consecutive time gap, s
C_{rb}	multilane roundabout capacity, veh/h
t_{min}	minimum time gap between two vehicles in the circulatory roadway, s
n_{cl}	number of circulatory lanes, -
n_{el}	number of entry lanes, -
M_{return}	volume of vehicles performing a U-turn movement in the roundabout, veh/h
M_{left}	left-turn traffic volume, veh/h
M_{right}	right-turn traffic volume, veh/h
t	simulation time, s
s_a	speed of each agent, km/h
d_a	travelled distance of each agent, m
t_s	time in the system of each agent, s
t_a	agent entry/start time, s
MAE	mean absolute error
RMSE	root mean square error
R^2	coefficient of determination
APC	article processing charge

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