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INNOVATIVE SMART AND SELF-REGULATING ROUNDABOUTS

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This paper presents two innovative smart roundabouts: the SSF-Roundabout (Smart Self-Regulating Roundabout) and the COM-Roundabout (Commutable Roundabout), designed for mixed traffic conditions involving Human-Driven Vehicles (HDVs) and Connected Autonomous Vehicles (CAVs). These novel road intersections employ adaptive control mechanisms that can dynamically adjust their configuration in response to varying traffic flow levels. SSF-Roundabout employs LOS (Level of Service) threshold-based adaptive flexible right-turn bypass lane activation, while COM-Roundabout adaptively adjusts the number of entry and circulating lanes to maximize capacity and minimize delays. The simulations confirm that both configurations provide substantial performance improvement compared with the conventional roundabout, as shown in particular by the results of the COM-Roundabout, described in detail, albeit at the expense of capacity/safety trade-offs. Finally, it is inferred that smart and self-regulating roundabouts are scalable solutions for future urban mobility systems.

Keywords: Smart roundabouts, CAVs, HDVs, capacity, safety analysis, adaptive control systems

1. Introduction

In recent years, many efforts have been made to reduce road accidents; however, these collisions still cause numerous deaths annually, with an estimated 1.19 million fatalities worldwide each year (World Health Organization, 2023). Therefore, one of the critical objectives in transportation studies and technical applications is to improve safety. The increasing advancement of technology and demonstration of the effectiveness of the use of artificial intelligence in various sectors have led to a new look towards the development of innovative designs aimed at simultaneously improving the safety, capacity and performance of transportation systems with a focus on road and railway infrastructures (Corriere *et al.*, 2015; Guerrieri and Ticali, 2012), technology, and traffic regulations. Among the various components of the urban transportation network, intersections are one of the most crucial elements, having a significant impact on safety, efficiency, and capacity. However, despite recent efforts to improve safety, they continue to account for a substantial proportion of urban road traffic accidents (Khanmohamadi and Guerrieri, 2025). In this context, conventional and innovative roundabouts can reduce conflict points and improve road safety, making them among the most widely used at-grade intersections (Guerrieri and Mauro, 2012). According to several studies, converting signalized or unsignalized intersections into roundabouts can significantly decrease the frequency and severity of crashes (Gross *et al.*, 2013; Tollazzi *et al.*, 2020; Guerrieri and Khanmohamadi, 2024; Zhou *et al.*, 2021). Such conversions can even reduce fatal crashes by up to 65% and injury-related crashes by up to 40% (Elvik, 2017). Lower vehicle speeds, conflict points among vehicle streams and smoother traffic flow can be cited as reasons for this safety improvement, facilitated by the simple geometric design of roundabouts.

Capacity limitations, especially in high or fluctuating traffic demand levels, can be cited as a major weakness of roundabouts, which can affect their adoption when the total inflow is exceptionally high. Despite improving safety by compact geometry and a limited number of conflict points, the modest entry capacity of single-lane roundabouts limits their ability to handle heavy traffic levels (Chen and Hourdos, 2018; Song *et al.*, 2022). In contrast, while multi-lane roundabouts achieve higher capacity, the accident risk will be increased by the relatively complex manoeuvres and additional conflict points (Zubaidi *et al.*, 2020; Bai *et al.*, 2021). The growing interest in smart roads (Guerrieri, 2021), particularly in urban contexts, has led to the introduction of innovative and new roundabout designs that can dynamically adapt their configurations to traffic flow conditions. In addition, recent advances in vehicle automation and communication technologies, particularly the emergence of connected and autonomous vehicles (CAVs), have created an ideal opportunity to improve intersection performance. In this regard, CAVs will be able to help optimize control strategies and improve traffic coordination by sharing real-time data with surrounding vehicles and infrastructures. In this context, two innovative roundabout types, COM-Roundabout (Commutable Roundabout) and SSF-Roundabout (Smart Self-regulating Roundabout with Bypass Lanes), have been proposed to address the limitations of traditional roundabouts' performance. The COM-Roundabout introduces a flexible layout that allows the number of entry and circulating lanes to be modified in real-time based on current traffic demand, supported by smart cameras, LED road markers, and Variable Message Signs (VMS). The SSF-Roundabout (Guerrieri and Khanmohamadi, 2025a), by contrast, focuses on dynamically activating or deactivating right-turn bypass lanes to optimize capacity while minimizing conflict points. Both systems rely on sensor-based detection, real-time traffic flow analysis, and adaptive control logic to enhance performance under mixed traffic conditions involving both Human-Driven Vehicles (HDVs) and CAVs. Although they have been founded on distinct approaches, such as lane commutation and bypass regulation, these two innovative roundabouts share a common goal: the simultaneous optimisation of adaptive and intelligent intersection protocols for performance improvement and safety enhancement. This article aims to merge the findings of both approaches and provide a comparative analysis under different traffic scenarios. Through the combination of findings from simulation and analytical models, this study illustrates the potential of adaptive roundabouts to enable more responsive, efficient, and safe road infrastructure in the future. Following these advances, self-regulating roundabouts have been introduced as a means of dynamically balancing safety and capacity. This short paper is organized into five parts. Section 2 describes the concept of Smart and Self-Regulating "SSF-Roundabouts", emphasizing its main characteristics, operational rationale, and implications for performance. Section 3 expands on this basis by introducing the COM-Roundabout - a novel, commutable, self-regulating type of roundabout - specially designed to accommodate a mix of HDVs and CAVs, complemented by an extensive discussion on capacity, delay and LOS evaluations. Section 4 presents the results of simulations related to the COM-Roundabout in various traffic and layout scenarios. Finally, Section 5 concludes the study with key findings and implications for the future of smart roundabout systems.

2. Smart and self-regulating SSF roundabouts: Concept and features

The traditional single-lane roundabouts improve safety by slowing traffic and minimizing conflict points, but due to inflexibility, they may generate poor levels of service (LOS) in the case of high traffic demand levels (Eva and Andrea, 2017). Right-turn bypass lanes at roundabouts can reduce congestion by isolating turning traffic streams; however, they introduce new conflict zones that may compromise the safety of pedestrians and cyclists (Dabbour and Easa, 2008; Savolainen *et al.*, 2023). Concurrently, studies demonstrate that CAVs have the potential to increase capacity and decrease delay through enhanced response times and coordinated motion; however, they require infrastructure that supports real-time sensing and communication with other vehicles and physical infrastructures. The Smart and Self-Regulating Single Lane roundabout with flexible bypass SSF-Roundabout (Guerrieri and Khanmohamadi, 2025a; Figure 1a) integrates the advantages of single lane and "flower" type roundabouts (Tollazzi *et al.*, 2011) while mitigating their respective drawbacks. The SSF-Roundabout utilises advanced vehicle detection and tracking systems, smart cameras, and loop detectors installed on each approach to monitor traffic volumes and queue lengths in real time continuously with the use of computer vision and deep-learning based-algorithms (Guerrieri *et al*., 2013; Guerrieri *et al*., 2024). It features adaptive bypass activation, whereby right-turn bypass lanes are dynamically enabled or disabled based on instantaneous demand and predefined LOS thresholds. It provides dynamic driver guidance through VMS and LED road markers, which indicate whether the bypass lanes are currently active or inactive. They are based on a cyclical control system with continuous control starting from data acquisition, through continuously monitoring approach streams and circulating traffic using detectors and cameras, which are fed into the roundabout for traffic flow evaluation, where the existing Origin–Destination (O/D) matrix is calculated and important psychotechnical driver parameters like critical gap and follow-up time are estimated in real-time. Subsequently, the decision logic system compares the actual LOS to set thresholds, initiating the opening of bypass lanes if delays pass above tolerable limits. After a decision has been made, driver guidance systems notify oncoming traffic of the bypass status through VMS and LED markers. Finally, the system reassesses traffic conditions every few seconds and dynamically sets lane configurations based on fluctuating demand. The SSF-Roundabout offers several important advantages: by enabling right-turn bypass lanes to be opened on demand, it controls capacity dynamically to maximize peak-period flow, and defaults to single-lane use during low-demand periods to limit conflict points and enhance safety. Additionally, its real-time streams of data prepare it for future coordination with connected vehicles, providing increased capacity gains. These benefits come at a price, though, as bringing in the sensors, communication systems, and dynamic signs required demands significant investment, and running the system relies on robust detection and control software to eliminate false alarms. Furthermore, drivers must learn to react correctly to VMS indications, respecting the imposed and signalled traffic rules.

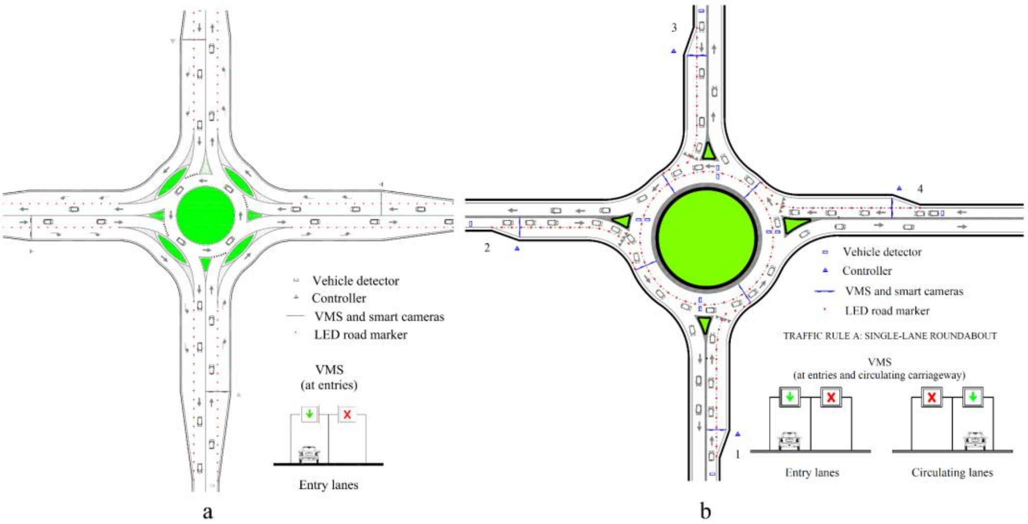


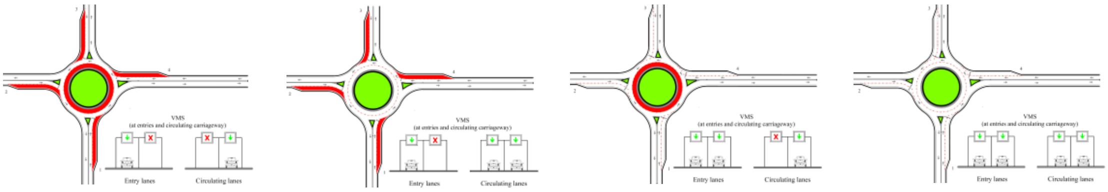
Figure 1. Layout of Smart and Self-Regulating Roundabouts: (a) SSF-Roundabout (b) COM-Roundabout

3. COM-roundabout: A commutable smart roundabout for HDVs and CAVs

The COM-Roundabout (Figure 1b) is a new “commutable” layout that dynamically changes both entry and circulation lanes in real-time, as a function of traffic demand and vehicle composition estimated in real-time. In contrast to fixed single- or multi-lane roundabout types, the COM-Roundabout can be configured in various ways. They can be switched from a single-lane roundabout (to limit conflict points during low demand) to a full two-lane configuration (to maximize capacity during high flows) and vice versa, with several additional roundabout configurations. This dynamic adjustment is carried out without interrupting traffic flows, as happens in signalized roundabouts, that is, retaining the continuous flow benefits of modern unsignalized roundabouts. This configuration was initially studied and evaluated in Guerrieri and Khanmohamadi (2025b). The COM-Roundabout is built upon three integrated components: advanced detection hardware—inductive loop detectors and smart cameras installed upstream of each approach to count vehicles, distinguish HDVs from CAVs, and estimate queue lengths; an intelligent control unit—a traffic manager system that continuously computes the origin -destination traffic matrix ($M_{O/D}$ matrix), assesses psychotechnical driver parameters such as critical gap and follow-up time, and selects the optimal lane configuration for each arm and circulating carriageway; and user-guidance interfaces—LED road markers and Variable Message Signs that instantly inform drivers which lanes are active and direct them into the correct entry and circulatory lanes.

Periodically, every few seconds, the COM-Roundabout runs a quick control loop in which it reads instant traffic flow conditions by observing current flow rates and CAV-to-HDV proportions, then updates its $M_{O/D}$ matrix estimates and computes measures of importance such as capacity, LOS, and queue lengths. It then compares the measured LOS with target values and selects one of 56 lane-activation options, allowing the activation of one or two lanes at each entrance and on the circulating carriageway (Guerrieri and Khanmohamadi, 2025). The system then promptly informs drivers of the active configuration, which employs VMS and LED pavement markers, before re-measuring traffic levels and adjusting again as conditions evolve. This independent, arm-by-arm option—for instance, keeping Arm 1 single-laned while Arm 3 has two entry lanes—ensures that capacity is carefully aligned with localized demand patterns. For clarity and comparison purposes, the four main geometric and lane configuration types of the COM-Roundabout, illustrated in Figure 2, are henceforth referred to as Scenario 1 through Scenario 4, as follows:

- Scenario 1: one entry lane – one circulating lane (i.e. the so-called single-lane roundabout);
- Scenario 2: one entry lane – two circulating lanes;
- Scenario 3: two entry lanes – one circulating lane;
- Scenario 4: two entry lanes – two circulating lanes (i.e. the double-lane roundabout).



(a) (b) (c) (d)

Figure 2. Dynamic lane configuration scenarios in the COM-Roundabout. (a) Scenario 1, (b) Scenario 2, (c) Scenario 3, and (d) Scenario 4 (adapted from Guerrieri and Khanmohamadi, 2025b)

The capacity analysis of the COM-Roundabout is primarily based on models from the HCM (7th Edition), particularly employing gap-acceptance theory to determine entry lane capacities. The entry capacity (c_i) depends on the circulating flow ($q_{c,i}$), the critical gap (t_c), and the follow-up time (t_f), and it is generally expressed as $c_i = f(q_{c,i}, t_c, t_f)$. More precisely, the relationship is commonly expressed as $c_i = A{\cdot}e^{-B{\cdot}q_{c,i}}$, with coefficients A and B determined by geometric conditions. For the different configurations under analysis, the following equations can be applied:

- Scenario 1: the COM-Roundabout is configured as a single lane roundabout (Figure 2a):

$$c_i = 1380e^{(-1.02\cdot10^{-3})\cdot q_{c,i}}, \tag{1}$$

where c_i is the lane capacity (veh/h) and $q_{c,i}$ is the conflicting flow rate in front of the arm i (veh/h).

- Scenario 2: the COM-Roundabout is configured with one-lane entries conflicted by two circulating lanes (Figure 2b):

$$c_i = 1420e^{(-0.85\cdot10^{-3})\cdot q_{c,i}}, \tag{2}$$

where $q_{c,i}$ is the total conflicting flow rate of both circulating lanes in front of the arm i.

- Scenario 3: the COM-Roundabout presents two-lane entries conflicted by one circulating lane: (Figure 2c):

$$c_i = 1420e^{(-0.91\cdot10^{-3})\cdot q_{c,i}}. \tag{3}$$

- The COM-Roundabout is configured with two-lane entries conflicted by two circulating lanes: (Figure 2d).

$$c_{i,R} = 1420e^{(-0.85\cdot10^{-3})\cdot q_{c,i}}, \tag{4}$$

$$c_{i,L} = 1350e^{(-0.92\cdot10^{-3})\cdot q_{c,i}}, \tag{5}$$

where, $c_{i,R}$ and $c_{i,L}$ represent the capacities (veh/h) of the right and left entry lanes of the i-th arm, respectively, while $q_{c,i}$ denotes the total conflicting flow rate (veh/h) from both circulating lanes opposing the i-th arm. The entry capacity of the arm can be estimated with the following relationship:

$$c_i = \frac{c_{i,R}+c_{i,L}}{\max\left(\frac{q_{e,i,R}}{c_{i,R}};\frac{q_{e,i,L}}{c_{i,L}}\right)}, \tag{6}$$

where $q_{e,i,R}$ and $q_{e,i,L}$ are the entry flows from the right and left lanes, respectively.

The total capacity C_{TOT} of the roundabout can be calculated with the relationship:

$$C_{TOT} = \sum_{i=1}^{N} c_i, \tag{7}$$

where c_i is the capacity of the arm i-th and N is the number of arms (for the case under consideration N = 4).

Delays of each lane are estimated with the following general relationships:

$$d = \frac{3600}{c_i} + 900\cdot T\cdot\left[x_i - 1 + \sqrt{(x_i-1)^2 + \frac{\frac{3600}{c_i}\cdot x_i}{450\cdot T}}\right] + 5\cdot\min[x_i,1], \tag{8}$$

where d represents the mean control delay per vehicle for the analysed entry lane (s/veh), x_i is the volume-to-capacity ratio (entry flow divided by entry capacity) of the subject lane, c_i is the lane's entry capacity (veh/h), and T indicates the analysis time period. The control delay d_i for the i-th approach with two lanes (right and left) is determined by calculating a volume-weighted average of each lane's delay, expressed as:

$$d_i = \frac{d_{e,i,R} \cdot q_{e,i,R} + d_{e,i,L} \cdot q_{e,i,L}}{q_{e,i,R} + q_{e,i,L}}, \tag{9}$$

where $d_{e,i,R}$, $d_{e,i,L}$ $q_{e,i,R}$ and $q_{e,i,L}$ are the delays and entry flows from right and left lanes, respectively. Finally, the mean control delay for the entire intersection (d_{int}) is estimated as:

$$d_{int} = \frac{\sum_{i=1}^{N} d_i \cdot q_{e,i}}{\sum_{i=1}^{N} q_{e,i}}. \tag{10}$$

The integration of CAVs in traffic flows necessitates the inclusion of adjustment factors f_A and f_B, which modify the base capacity equation. In this case, the formula is:

$$c_i = f_A \cdot A \cdot e^{-f_B \cdot B \cdot q_{c,i}}. \tag{11}$$

Detailed explanations of the adjustment factors f_A and f_B are provided in the HM 7th edition. To evaluate the safety performance of the COM-Roundabout, the study adopted the predictive crash models from NCHRP Report 888, which combine Safety Performance Functions (SPFs) with Crash Modification Factors (CMFs). The expected annual crash frequency (ACF) is calculated as:

$$ACF = C \cdot N_{SPF} \cdot (CMF_1 \cdot CMF_2 \cdot ... \cdot CMF_n), \tag{12}$$

where C represents a calibration coefficient (assumed to be 1 in this theoretical analysis without empirical data from real-world applications), N_{SPF} is the predicted base crash frequency, and CMFs incorporate adjustments for site-specific geometric and traffic conditions. Separate SPF equations are applied for a single-lane layout (Scenario 1, by Eqs. (13)) and multi-lane layout (Scenario 4, by Eqs. (14)):

$$N_{SPF} = \exp\left[-3.503 + 0.915 \cdot LN(EntAADT/1000) + 0.206 \cdot I_{rural}\right]. \tag{13}$$

$$N_{SPF} = \exp\left[-3.535 + 1.276 \cdot LN(EntAADT/1000) + 0.250 \cdot I_{rural}\right]. \tag{14}$$

The inscribed circle diameter (ICD) is incorporated through the crash modification factor $CMF_{ICD} = \exp\left[-0.00621(ICD-125)\right]$.

4. Simulations and results

In this study, approximately one million traffic test conditions were created and examined based on the type of COM-Roundabout configuration (diameter D = 50 m), the traffic flow entering each entry lane and circulator lane, and the CAV percentage. Under all analyzed traffic conditions, we assume the circulating and exit lanes consistently operate in undersaturated states (x= flow/capacity < 1). Therefore, congestion events can only occur when entry lanes are saturated or oversaturated. This study excludes consideration of transient operational traffic states. Considering the arms illustrated in Figure 1b, and the time instant t, the traffic demand is represented by the origin-destination matrix $M_{O/D}(t)$ expressed in the vector form:

$$M_{O/D}(t) = [Q_{ij}(t)] \qquad \text{with } i, j = 1, 2, 3, 4, \tag{15}$$

where $Q_{ij}(t)$ represents the traffic volume (veh/h) entering from arm “i” and exiting from arm “j” of the roundabout at time t.

Considering Q_{ij} as the design hourly volume from entry arm i to exit arm j, the following relationship between Q_{ij} and the Annual Average Daily Traffic $AADT_{ij}$ can be established:

$$Q_{ij} = \alpha \cdot PHF \cdot AADT_{ij}. \tag{16}$$

The parameter α is the ratio between Q_{ij} and $AADT_{ij}$, with typical values for urban roads ranging from 0.08 to 0.10 based on empirical observations. The peak hour factor (PHF) is defined as the ratio of the peak 15-minute flow rate to one-fourth of the hourly flow rate, typically ranging from 0.90 to 0.95 for urban roadways with high traffic volumes. In this research, conservative parameter values of $\alpha = 0.10$ and PHF = 0.90 were selected to account for potential traffic variability. Finally, the total entry flow (i.e. the total inflow) at COM-Roundabout is calculated as the sum of the flow components:

$$Q_{TOT} = \sum_{i,j} Q_{i,j}. \tag{17}$$

The main results of the simulations are summarized in Figures 3-8.

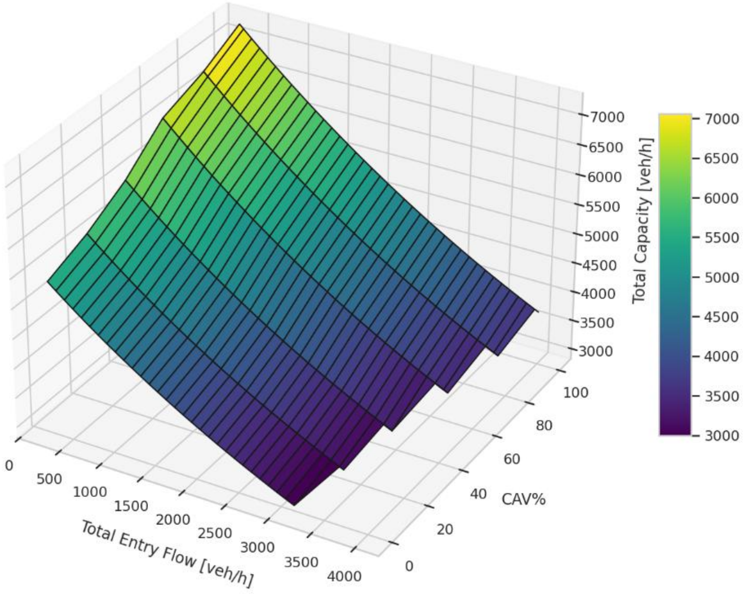


Figure 3. Impact of CAV penetration rate and Total Entry Flow on COM-Roundabout Capacity (Scenario 4)

The adaptive, commutable design of the COM-Roundabout offers significant benefits over static single- and multi-lane roundabouts by optimizing capacity and safety to meet prevailing traffic demand. During periods of low traffic demand, the potential to return to a single-lane operation reduces the number of conflict points. It thus maintains the typical low accident rates of single-lane roundabouts. On the other hand, during heavy flow conditions, with or without high CAV penetration rates, the system may engage additional lanes to increase capacity, lowering average delays significantly and enhancing LOS in most instances (Guerrieri and Khanmohamadi, 2025). Regarding Figure 3, increasing CAV penetration rates, particularly under moderate total entry flow, improves capacity, reflecting a synergistic benefit of automation. Increasing the CAVs' usage share enables the system to mitigate the adverse effects of the growing entry flow rate on the roundabout capacity. However, such increases in performance are accompanied by corresponding increases in the risk of crashing as the number of conflict points increases. The results indicate that the predicted crash frequency increases from fewer than 1 crash/year when the COM-Roundabout is in single-lane mode up to and beyond 2 crashes/year when it is in the fully two-lane mode. Crash frequency rises quasi-linearly with AADT, more steeply for the scenario in which the COM-Roundabout is configured as a double-lane roundabout (Scenario 4, Figure 4).

According to Figure 5, in all LOS categories, the crash frequency of the double-lane mode (Scenario 4) is higher than the single-lane mode (Scenario 1). With each step of decreasing LOS, the distance between crash frequencies of these two types of COM-Roundabout configuration increases significantly, so that at LOS A the difference is about 133%, which increases excessively to 170–180% at LOS D to F. From a safety viewpoint, it is essential to consider the development of a real-time optimization plan to optimize safety and performance in different traffic flow conditions. However, in both configurations, delay decreases as capacity increases, indicating the effect of increasing capacity on operational performance improvement (Figure 6).

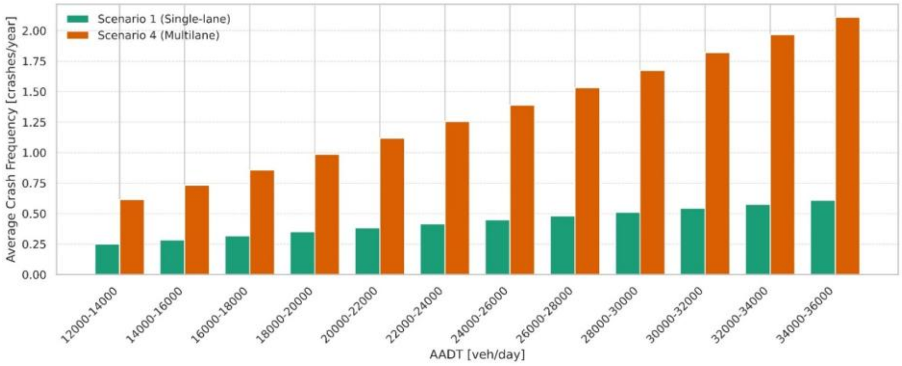


Figure 4. Average Crash Frequency as a function of AADT for Scenario 1 and Scenario 4

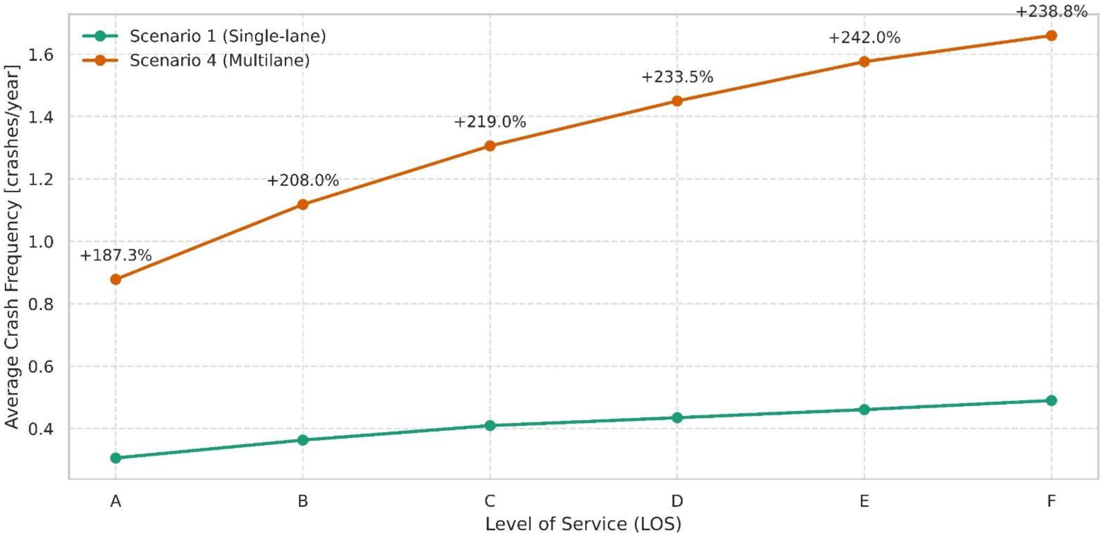


Figure 5. Impact of LOS on Crash Frequency: Scenario 1 vs Scenario 4

As shown in Figures 6 and 7, although the control delay improves (due to the increase in total capacity), a conflicting relationship is observed between safety and capacity, evaluated for a CAVs penetration rate of 0%. Crash frequency increases with delay, particularly in multi-lane roundabouts, accentuating the safety advantage of single-lane configurations. This supports the importance of strategically limiting two-lane operations to short traffic peak periods or the most solicited entries, thus creating a balance between safety and efficiency. Furthermore, Figure 8 indicates that CAV deployment improves traffic performance and LOS, particularly in moderate to high-demand conditions.

From a deployment perspective, COM-Roundabout requires robust communication and detection systems, as well as control algorithms. Sensor failures or misclassifications can cause the wrong lane to be activated; hence, robust validation and fail-safe modes are necessary. Moreover, drivers' adherence to dynamic road signs needs to be closely monitored and supported by clear, redundant guidance, such as road-surface LEDs and overhead Variable Message Signs (VMS).

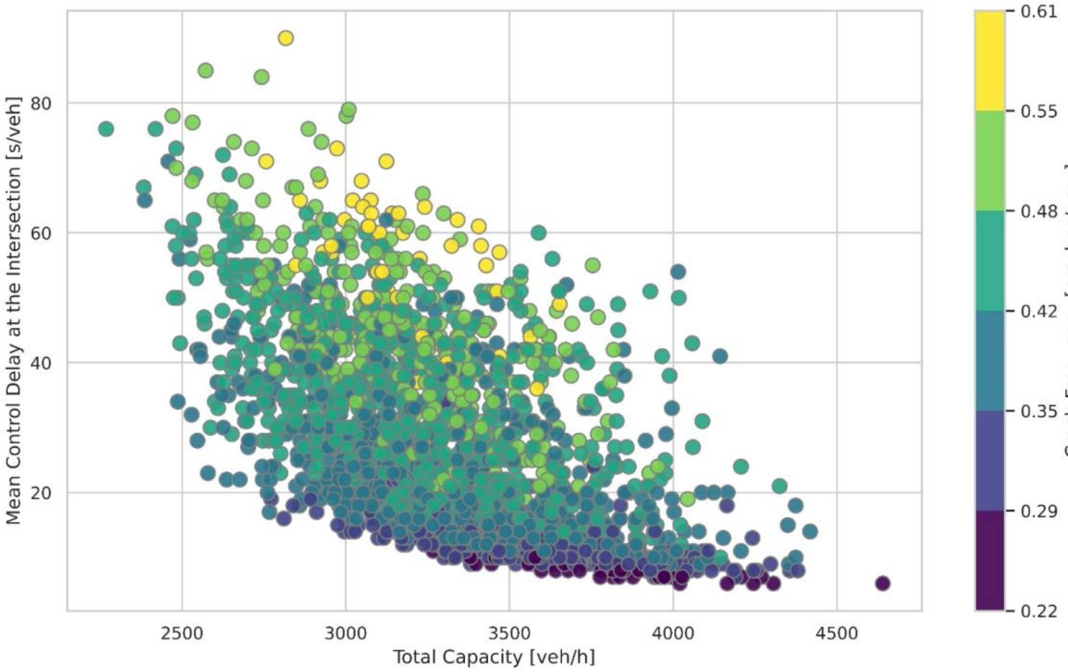


Figure 6. Capacity vs Mean Delay and expected Crash Frequency for the COM-Roundabout – Scenario 1 (CAVs = 0%)

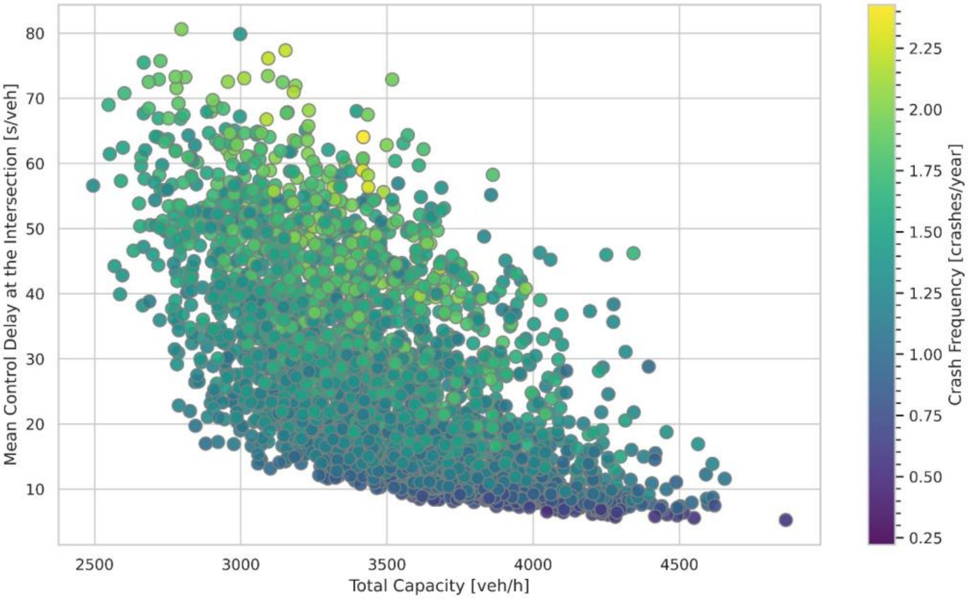


Figure 7. Capacity vs Mean Delay and expected Crash Frequency for the COM-Roundabout – Scenario 4 (CAVs = 0%)

Finally, while our one-million-$M_{O/D}$(t) simulation suite provides strong evidence of the new roundabout concept's versatility, real-world pilot deployments will be critical to validate performance under stochastic traffic patterns, mixed-fleet behavior, and transient demand surges. Future work should also explore the integration with centralized traffic management systems, dynamic priority schemes for CAVs and HDVs, and the potential for vehicle-to-infrastructure coordination to reduce accident risk further and enhance capacity.

It should be noted that a similar methodological approach to the study of functionality and safety can also be adopted for the case of SSF-Roundabout (Figure 1a), the evaluations of which are not reported here for reasons of synthesis. For more details on the SSF-Roundabout, the interested reader may consult Guerrieri and Khanmohamadi (2025a).

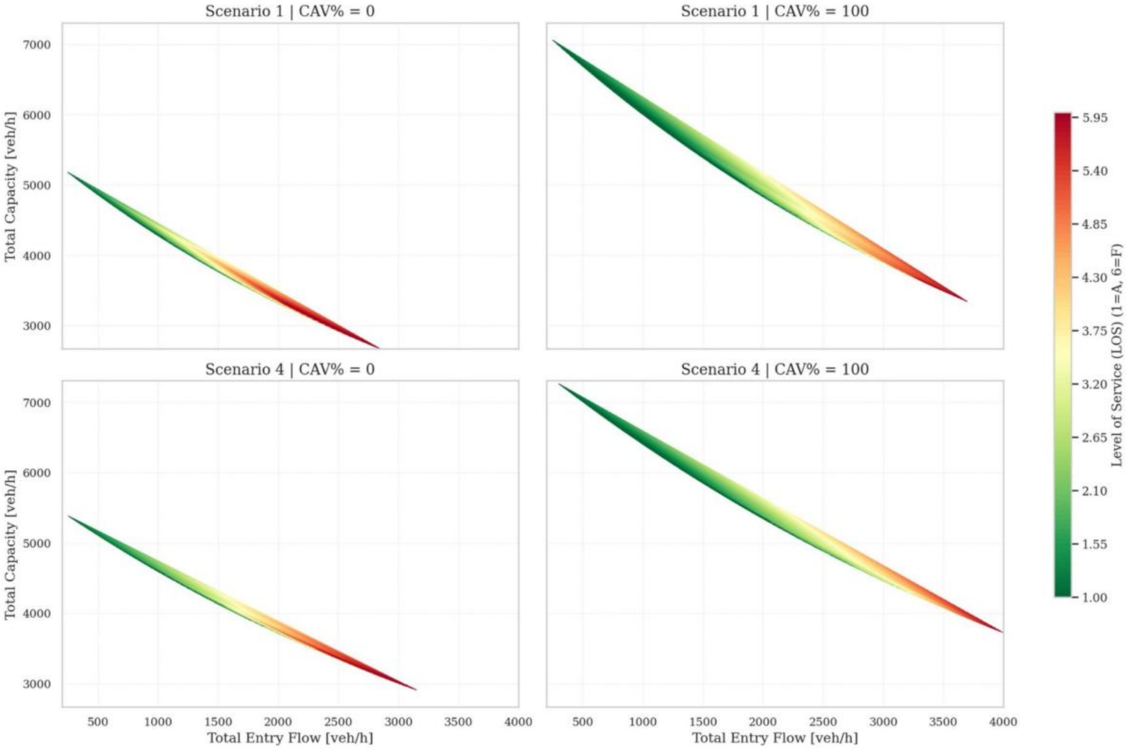


Figure 8. Comparative LOS Contour Maps for Scenario 1 and Scenario 4 under CAV% = 0% and CAV% = 100%

5. Conclusions

This study investigated two smart and self-regulating roundabouts, specifically the COM-Roundabout and SSF-Roundabout, in shattering the limitations of conventional roundabout designs from the safety and capacity perspectives. The novel roundabout types use real-time traffic information, adaptive control strategies, and dynamic infrastructure to maximize their performance in various operational conditions, including mixed fleets of HDVs and CAVs.

The main findings highlight the COM-Roundabout's potential benefits, including dynamic lane configuration adjustment, capacity gains during peak hours through multi-lane operation, and the preservation of safety through single-lane operation during low-demand hours. Analogously, the SSF-Roundabout noted appreciable capacity improvements through adaptive right-turn bypass lane usage, which minimised delays and improved LOS. Both designs, nevertheless, involve sensitive trade-offs between capacity improvement and safety, since multi-lane operation has the potential to boost conflict points and crash risk. In short, the success of these systems relies on three key factors:

- effective sensor and communications technologies for accurate real-time data collection and system responsiveness;
- clear and reliable driver guidance through dynamic signing (i.e., LED markings and VMS) to avoid confusion and foster compliance;
- strategic deployment of multi-lane configurations to achieve maximum efficiency and safety, especially at peak traffic volumes.

Future investigations will focus on evaluating transient traffic conditions, rather than solely steady-state conditions, as has been done so far. It is highlighted that further development of technology for general vehicle-to-infrastructure (V2I) coordination will yield even greater safety and efficiency benefits, especially with high CAV penetration.

In conclusion, COM-Roundabout and SSF-Roundabout could be revolutionary advances in adaptive, smart road infrastructures. By striking a balance between performance and safety, the systems offer a scalable solution to contemporary urban mobility challenges, paving the way for smarter, more responsive road networks in the era of autonomous and connected vehicles.

Declaration of Generative AI and AI-assisted technologies in the writing process:

During the preparation of this manuscript the authors did not used Generative AI and AI-assisted technologies and take full responsibility for this declaration.

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