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Research Paper

COM-Roundabout: The first smart commutable and self-regulating roundabout for HDVs and CAVs

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ABSTRACT

In the last decades, many new types of roundabouts and traffic regulation systems have been introduced in several countries. However, some issues related to their performance and safety remain. This article presents a new concept of self-regulating smart roundabout recently ideated: the COM-Roundabout (Commutable Roundabout), where the number of active entry and circulating lanes is dynamically adjusted in real time depending on the measured traffic demand intensity. The COM-Roundabout utilizes vehicle and queue detectors, smart cameras, LED road markers, and Variable Message Signs (VMS) to guide traffic into appropriate lanes dynamically. Performance in terms of capacity, delay, level of service and predicted accident rates is evaluated in many traffic scenarios, based on an extensive dataset of one million Origin-Destination traffic matrices ($M_{O/D}$), considering both Human-Driven Vehicles (HDVs) and Cooperative Autonomous Vehicles (CAVs), applying robust and widely used estimation methods (HCM and HSM models). This research demonstrates that the COM-Roundabout could be used to optimise real-time performance (e.g. capacity and LOS) and safety thanks to the numerous layouts and traffic control programmes adaptable to specific traffic conditions.

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1. Introduction

Intersections play a crucial role in the functionality and safety of all road networks. Usually, road intersections are classified into two-way stop control (TWSC), all-way stop control (AWSC), signalized (SIG) and roundabout (RAB) (Arshi et al., 2018; MUTCD, 2023). A roundabout is a type of at-grade intersection that has been shown to enhance safety compared to other unsignalized intersections (Orsini, et al., 2019). Extensive research demonstrates that under specific traffic demand levels, roundabouts can reduce delays and congestion (Burdett et al., 2017). Safety conditions are guaranteed by the geometric layout, which reduces the number of conflict points with respect to the other unsignalized intersections (Persaud et al., 2001), as well as by the moderate travel speed of each maneuver. Safety analyses obtained from crash data have shown that converting unsignalized intersections to roundabouts is associated with a remarkable reduction in fatal accidents of about 65% and a reduction in injury accidents of about 40% (Elvik, 2017). Also, converting signalized intersections to roundabouts can produce a significant reduction in both total and injury crashes (Gross, et al, 2013). While roundabouts generally improve safety, their integration into a road network requires accurate capacity predictions, which is the most important

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Nomenclature

A	parameter of the entry capacity model
Ac	lane active
AADT	sum of the annual average daily traffic that enters from all legs
ACF	predicted average crash frequency
B	parameter of the entry capacity model
CAVs	Cooperative Autonomous Vehicles
c_i	entry capacity of the i-th arm
$c_{i,R}$	capacity of the right lane in cases of two entry lane scenarios
$c_{i,l}$	capacity of the left lane in cases of two entry lane scenarios
COM	Commutable
CMFs	Crash Modification Factors
C_{TOT}	total capacity of the roundabout
$d_{e,i,R}$,	control delay of the right lane in cases of two entry lane scenarios
$d_{e,i,L}$	control delay of the left lane in cases of two entry lane scenarios
d_i	control delay of the i-th approach in cases of two entry lane scenarios
d_{int}	control delay for the entire roundabout
f_A	adjustment factor (intercept parameter) of the entry capacity model for taking into consideration flows of CAVs
f_B	adjustment factor (slope parameter) of the entry capacity model for taking into consideration flows of CAVs
HDVs	Human-Driven Vehicles
I	lane inactive
ICD	inscribed circle diameter of the roundabout
I_{rural}	area type indicator variable
LOS	Level of Service
$M_{O/D}$	Origin-Destination traffic matrix
$M_{O/D}(t)$	Origin-Destination traffic matrix at the time instant t
N	number of arms of the roundabout
N_{SPF}	predicted average crash frequency for base conditions
PHF	Peak Hour Factor
Q	queue
$q_{c,i}$	circulating flow in front of the i-th arm
$q_{e,i,\ R}$	entry flow from the right lane in cases of two entry lane scenarios
$q_{e,i,\ L}$	entry flow from the left lane in cases of two entry lane scenarios
$q_{e,i}$	entry flow from the i-th arm
$Q_{ij}(t)$	traffic volume that enters from the arm i and exits from the arm j at the time instant t
SPF	Safety Performance Function
T	time interval period for estimating delays and queues
t_c	critical gap
t_f	follow-up time
VMS	Variable Message Signs
x	degree of saturation of the analysed lane

performance measure for predicting delay, queue and Level of Service (LOS) (Chen and Hourdos, 2018). There are different definitions of roundabout capacity but the most used is related to the maximum value of flow that an entry can accommodate during a set time interval. Capacity depends mainly on the circulating flow around the roundabout that conflicts with the entry flow, geometric layout and drivers' behaviour. Most of the used capacity models are either analytical, founded on the so-called gap acceptance theory, or empirical regression that employs observed geometric and traffic flow variables (Al-Madani, 2022). In addition, capacity and other measures of effectiveness (MOEs) can be assessed from microscopic traffic simulations by using commercial software like Aimsun, Vissim, Sumo, etc., which are founded principally on the car-following theory. However, microscopic traffic simulations involve several phases (Barcelo, 2010) including: (1) project scope; (2) package selection; (3) data assembly and input; (4) verification and calibration; (5) alternatives analysis and conclusions.

In 1966, modern roundabouts were introduced in the Road Traffic Act in the UK and, in successive decades, rapidly adopted in European countries and other places worldwide. Modern roundabouts can be classified into single and multi-lane roundabouts. The single-lane roundabout presents a single-lane entry at all arms and one circulatory lane. Instead,

multi-lane roundabouts have entries and/or circular carriageways with more than one lane. There are at least the following additional types (Guerrieri et al., 2015):

- *rotaries*: an old-style large circular intersection where weaving sections along the circulating carriageway are required between intersection arms. Entry, exit and circulating speeds are high due to the large diameter of the central island (NCHRP Report 672);
- *signalized roundabouts*: traffic signals are used to control one or more entry–circulating traffic flows. Queue storage segments within the circulatory and entry lanes are therefore required;
- *neighbourhood traffic circles:* roundabouts used at the intersections of local streets for reasons of traffic calmig and/or aesthetics (NCHRP Report 672);
- *turbo-roundabouts*: the lanes are usually physically delimited—at entry, exit, and on the ring—by insurmountable curbs. Such a peculiarity allows turbo-roundabouts to give rise to a lower number of potential conflicting points, a lesser driving speed, and safety improvement compared to multilane roundabouts but lower capacity (Gallelli et al. 2016);
- *signalized turbo-roundabouts:* traffic signals are implemented to control one or more entry–circulating traffic flows (Bai, et al., 2021);
- *spiral-Marking roundabouts*: spiral-type markings are depicted on the road pavement to illustrate the rules that vehicles exiting a roundabout have priority over vehicles in the outer circulating lane, and circulating vehicles have priority over any approaching vehicles (Wong, et al. 2012);
- *flower-roundabouts:* a roundabout with two lanes at entries, two lanes at exits and a ring lane which makes right-turning vehicles get onto a free-flowing right-turn bypass lane and not into the ring lane (Tollazzi et al., 2011; Tollazzi, 2015).

Choosing the proper type is a substantial concern in the planning phase of building a roundabout. Many studies have elaborated selection criteria for layout and traffic control systems, considering several traffic levels and other boundary conditions. Some research proves that roundabouts with signal control offer superior performance with high traffic demand levels than unsignalized ones. Regarding fully signalized roundabouts, two main control types are commonly used: leg-by-leg control and twice-stop-left-turn control (right-hand driving system) (Yang et al., 2004). However, for various reasons, single and multilane roundabouts remain the most used roundabout types (Tollazzi, 2015). Single-lane roundabouts generate lower conflict points and vehicle speeds, but capacity is relatively low (Brilon, 2005); instead, increasing the number of entry and circulatory lanes may increase the capacity but cause some key problems. For instance, the inner circulating lane is often under-utilized, and the number of conflict points increases, which increases the number of accidents. To overcome these problems, the novel *COM-Roundabout* (Commutable Roundabout) was designed (Guerrieri, 2024a,b). This is a commutable smart roundabout in which the number of usable entry and circulating lanes is not fixed, as in the aforementioned roundabout types, but can be modified in real time depending on the traffic demand level. Thanks to the use of vehicle counting systems and smart cameras, LED road markers and Variable Message Signs (VMS) (Lagoa, et al., 2024; Wu et al. 2024) installed on arms and circulating carriageways, the traffic streams are channelled into different lanes depending on the traffic flow rates and the desired minimum LOS at entries and the whole roundabout. This research introduces the concept of *COM-Roundabout*, considering both safety and performance in many traffic situations, taking into consideration the effect of Human-Driven vehicles (HDVs) and Cooperative Autonomous Vehicles (CAVs) (Anagnostopoulos and Kehagia, 2020; Chalaki et al, 2020; Tumminello et al., 2024). Because of its features, it is arguable that COM-Roundabouts could be incorporated into traditional and smart road infrastructures (Guerrieri, 2021; Vidyarthi et al., 2023) to alleviate congestion phenomena and safety issues. The results from this research in terms of MOEs and safety (estimated with well-known and largely used analytical models) show the potential advantages of this novel type of roundabout compared to traditional ones.

The rest of the article is organised as follows. Section 2 presents the main technical characteristics of the novel COM-Roundabout. Sections 3 and 4 describe the models used for performance and safety analysis. Section 5 briefly describes the input data used for the performance and safety simulations. In Section 6, results and discussion are presented. Finally, the conclusions of this study are summarised in Section 7.

2. COM-Roundabout: Basic characteristic

Due to their simplicity, traffic regulation systems, construction and maintenance costs, and safety and capacity levels, single and multilane roundabouts are widely used in urban and extra-urban road networks.

Single-lane roundabouts offer significant safety advantages because they have few conflict points between traffic streams, and their geometry forces drivers to moderate their speeds. On the other hand, they offer relatively low capacities and must be used only for modest traffic demand. In contrast, multi-lane roundabouts have much greater capacities than single-lane roundabouts but give rise to more accidents.

The COM-Roundabout integrates the advantages of single and multi-lane roundabouts while mitigating their limitations (Fig. 1).

The *COM-Roundabout* is a flexible and smart roundabout that combines and maximises the positive aspects of single and multi-lane roundabouts while minimizing their defects. Depending on the intensity and distribution of traffic (measured by vehicle detectors and smart cameras) among arms, each entry and the corresponding circulating carriageway can be automatically and in real-time modified in terms of the available number of lanes. Vehicle and queue detectors must be posi-

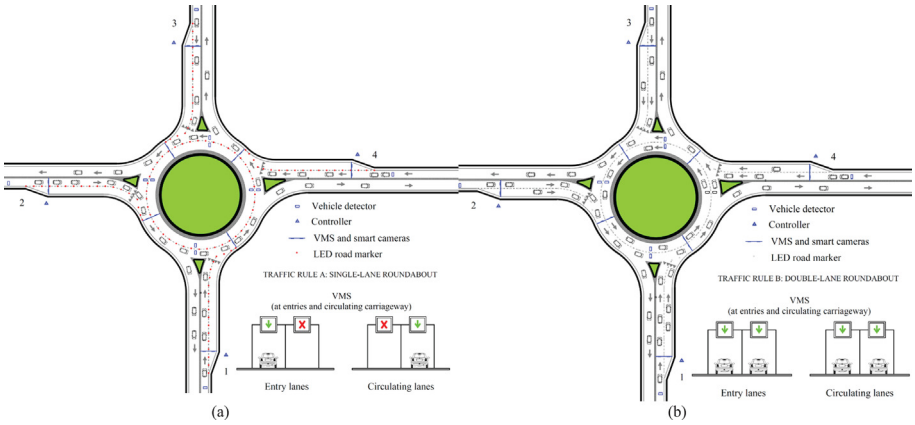

Fig. 1. COM-Roundabout. (a) Traffic rule A: only one entry lane and one circulation lane are active for each entry. The COM-Roundabout works as a single-lane roundabout. (b) Traffic rule B: for each entry, two lanes and two circulation lanes are active. The COM-Roundabout works as a double-lane roundabout.

tioned at the most appropriate section of the legs because this can impact the duration of queues at each entry. In this regard, the Manual of Traffic Roads and Use Management (TRUM, 2022) indicates installing vehicle counting systems (e.g. inductive loop detectors) at certain stopping distances from the upstream of the stop or yield line (e.g. 35 m, for a 50 km/h speed limit and 40 m for a 60 km/h speed limit) (Assolie et al., 2023).

In brief, the system works as follows (Fig. 2):

- Current traffic flow and queue length are extracted from smart video camera streams and vehicle detectors;
- System computes the traffic flow, estimates the Origin-Destination traffic matrix, the psycho-technical users' parameters (critical time and follow-up time) and schedule optimizes flow at the COM-Roundabout based on the worst admissible LOS of each entry (set by the Road Operator) and the Scenario is chosen according to Table 1;
- The controller communicates to the neighbouring VMS and LED road markers to indicate what lanes are activated;
- the layout Scenario is updated every few seconds and may change based on the estimated current Origin-Destination traffic matrix and desirable LOS;
- VMS and LED road markers indicate information to users to channel traffic steams correctly into entering and circulation lanes.

When traffic flows are low, LED road markers and VMS direct vehicles to a single lane (at the entries and on the ring). In this case, the COM-Roundabout works as a single-lane roundabout (Fig. 1a) and minimizes the risk of accidents, offering capacity values sufficient to accommodate the traffic flows arriving at the intersection.

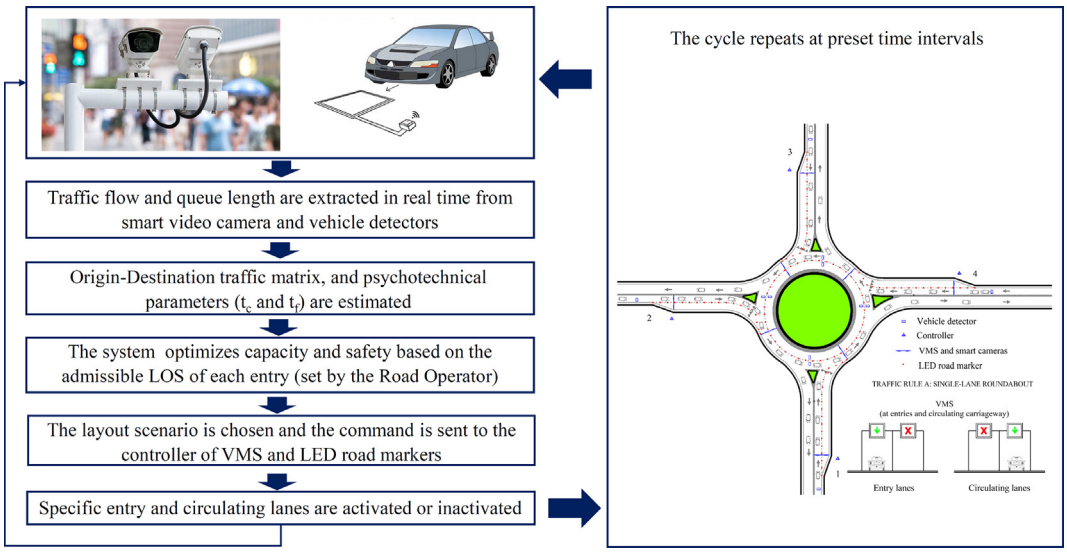

Fig. 2. How the COM-Roundabout works.

Table 1
Scenarios related to the activation or inactivation of entry and circulating lanes at COM-Roundabout (Ac: lane active, I: lane inactive).

Scenario	ENTRY No. 1								Scenario	ENTRY No. 3							
	One circulating lane Second entry lane				Two circulating lanes Second entry lane					One circulating lane Second entry lane				Two circulating lanes Second entry lane			
	Arm 1	Arm 2	Arm 3	Arm 4	Arm 1	Arm 2	Arm 3	Arm 4		Arm 1	Arm 2	Arm 3	Arm 4	Arm 1	Arm 2	Arm 3	Arm 4
S1	I	I	I	I	I	I	I	I	S29	I	I	I	I	I	I	I	I
S2	Ac	I	I	I	Ac	I	I	I	S30	Ac	I	I	I	Ac	I	I	I
S3	Ac	Ac	I	I	Ac	Ac	I	I	S31	Ac	Ac	I	I	Ac	Ac	I	I
S4	Ac	Ac	Ac	I	Ac	Ac	Ac	I	S32	Ac	Ac	Ac	I	Ac	Ac	Ac	I
S5	Ac	Ac	Ac	Ac	Ac	Ac	Ac	Ac	S33	Ac	Ac	Ac	Ac	Ac	Ac	Ac	Ac
S6	I	I	I	Ac	I	I	I	Ac	S34	I	I	I	Ac	I	I	I	Ac
S7	I	I	Ac	Ac	I	I	Ac	Ac	S35	I	I	Ac	Ac	I	I	Ac	Ac
S8	I	Ac	Ac	Ac	I	Ac	Ac	Ac	S36	I	Ac	Ac	Ac	I	Ac	Ac	Ac
S9	Ac	I	Ac	Ac	Ac	I	Ac	Ac	S37	Ac	I	Ac	Ac	Ac	I	Ac	Ac
S10	I	I	Ac	I	I	I	Ac	I	S38	I	I	Ac	I	I	I	Ac	I
S11	I	Ac	Ac	I	I	Ac	Ac	I	S39	I	Ac	Ac	I	I	Ac	Ac	I
S12	I	Ac	Ac	Ac	I	Ac	Ac	Ac	S40	I	Ac	Ac	Ac	I	Ac	Ac	Ac
S13	I	Ac	I	I	I	Ac	I	I	S41	I	Ac	I	I	I	Ac	I	I
S14	Ac	Ac	I	Ac	Ac	Ac	I	Ac	S42	Ac	Ac	I	Ac	Ac	Ac	I	Ac
Scenario	**ENTRY No. 2**								Scenario	**ENTRY No. 4**							
	One circulating lane Second entry lane				Two circulating lanes Second entry lane					One circulating lane Second entry lane				Two circulatingV lanes Second entry lane			
	Arm 1	Arm 2	Arm 3	Arm 4	Arm 1	Arm 2	Arm 3	Arm 4		Arm 1	Arm 2	Arm 3	Arm 4	Arm 1	Arm 2	Arm 3	Arm 4
S15	I	I	I	I	I	I	I	I	S43	I	I	I	I	I	I	I	I
S16	Ac	I	I	I	Ac	I	I	I	S44	Ac	I	I	I	Ac	I	I	I
S17	Ac	Ac	I	I	Ac	Ac	I	I	S45	Ac	Ac	I	I	Ac	Ac	I	I
S18	Ac	Ac	Ac	I	Ac	Ac	Ac	I	S46	Ac	Ac	Ac	I	Ac	Ac	Ac	I
S19	Ac	Ac	Ac	Ac	Ac	Ac	Ac	Ac	S47	Ac	Ac	Ac	Ac	Ac	Ac	Ac	Ac
S20	I	I	I	Ac	I	I	I	Ac	S48	I	I	I	Ac	I	I	I	Ac
S21	I	I	Ac	Ac	I	I	Ac	Ac	S49	I	I	Ac	Ac	I	I	Ac	Ac
S22	I	Ac	Ac	Ac	I	Ac	Ac	Ac	S50	I	Ac	Ac	Ac	I	Ac	Ac	Ac
S23	Ac	I	Ac	Ac	Ac	I	Ac	Ac	S51	Ac	I	Ac	Ac	Ac	I	Ac	Ac
S24	I	I	Ac	I	I	I	Ac	I	S52	I	I	Ac	I	I	I	Ac	I
S25	I	Ac	Ac	I	I	Ac	Ac	I	S53	I	Ac	Ac	I	I	Ac	Ac	I
S26	I	Ac	Ac	Ac	I	Ac	Ac	Ac	S54	I	Ac	Ac	Ac	I	Ac	Ac	Ac
S27	I	Ac	I	I	I	Ac	I	I	S55	I	Ac	I	I	I	Ac	I	I
S28	Ac	Ac	I	Ac	Ac	Ac	I	Ac	S56	Ac	Ac	I	Ac	Ac	Ac	I	Ac

When traffic flows increase, the activation of more lanes is required, and the system is switched to a multi-lane roundabout (Fig. 1b), with a consequent increase in capacity and reduction of delays and queues.

There are many other scenarios between these two extreme cases, as shown in Table 1. From time to time, depending on the situations present, each arm can work autonomously. So, there could be entries with only one active lane and others with two active lanes. Theoretically, this same procedure can concern the circulating lanes: the active or inactive ones could differ depending on the entry considered and the required capacity. Unlike signalized roundabouts, the COM-Roundabout regulates traffic without stopping vehicle flows. In short, the COM-Roundabout is an adaptive roundabout that regulates itself to changing traffic conditions, thus optimizing both the system's capacity and safety. In addition, in future traffic scenarios, CAVs will automatically deviate vehicle trajectories to the proper lanes employing a management area (MA). So, CAVs will give kinematic data to the COM-Roundabout manager, including their instantaneous position, speed, and acceleration, and receive the trajectory to follow according to the activated lanes (Mohebifard and Hajbabaie, 2022).

3. Performance analysis models

Capacity is a key factor in designing and analysing all transportation systems. (Corriere et al., 2013; Guerrieri & Ticali, 2012). In particular, capacity is the fundamental Measure of Effectiveness (MOEs) for the performance assessment of roundabouts. The other MOEs, such as delays, queues and levels of service (LOS), are functions of capacity and, therefore, can be estimated once the capacity is calculated. However, Capacity can be defined in various ways, including (Mauro, 2010; Guerrieri, 2024a,b):

- Entry capacity (EC), is the lowest entering flow value from an entry that produces the constant existence of vehicles queuing up to enter the circulating carriageway;

- Simple Capacity (SC), is the initial value of capacity that is reached at one entry for a steady increase of the traffic demand and for a prefixed proportion of the traffic streams at the road intersection;
- Total Capacity (TC) is the sum of the flows entering from entries, equivalent to the capacity of the corresponding entries for a given proportion of the traffic streams at the road intersection.

Simple Capacity and Total Capacity are derived from the Entry Capacity, which is generally estimated by gap acceptance traffic models, as the model presented in the current version of the Highway Capacity Manual (HCM 7th Edition, 2022). The gap acceptance models have a general form of the type:

$$c_i = f(q_{c,i}, t_c, t_f) \tag{1}$$

where capacity c_i is the entry lane capacity of the i-th arm, $q_{c,i}$ is the circulating flow in front of the i-th arm, t_c is the critical gap and t_f is the follow-up time. The letters are the so-called psychotechnical parameters of users, which must be derived from real traffic data using particular estimation procedures like the Drew, Raff, Ashworth and Miller techniques. (Mauro, 2010). The capacity model suggested by the HCM is derived from the Siegloch model (Siegloch, 1973):

$$c_i = Ae^{-B \cdot q_{c,i}} \tag{2}$$

$$A = \frac{3600}{t_f} \tag{3}$$

$$B = \frac{t_c - \frac{t_f}{2}}{3600} \tag{4}$$

As shown in Fig. 3, the values of t_f and t_c strongly influence the entry capacity, and therefore, it is essential to use appropriate and reliable values of these parameters during the performance analysis of new or existing roundabouts. Generally, a reliable estimate of the psychotechnical users' parameters is obtained through a statistical investigation of traffic data. However, this leads to identifying fixed values of t_f and t_c, which are then used as the basis for the performance analysis of roundabouts. Instead, t_c and t_f can vary over time, and therefore, the capacity of the entries can change significantly and continuously even with the same $q_{c,i}$ value. Consequently, traffic conditions or users different from those present in the samples used to estimate t_c and t_f can produce distorted results of capacity and, therefore, of LOS. From this point of view, the use of smart cameras in the COM-Roundabout along with the image processing techniques Deep learning algorithm for vehicle identification and tracking (Guerrieri et al., 2012; Guerrieri et al., 2013) may potentially allow a continuous evaluation of t_f and t_c (cf. Fig. 2) by adopting specific assessment techniques such as the Drew, Raff, Ashworth and Miller methods (Mauro, 2010), and then produce a more accurate estimation of the COM-Roundabout capacity over the time.

3.1. Entry and total capacity estimation

In this research, the HCM procedures have been implemented considered for the COM-Roundabout the following main scenarios (cf. Table 1) and under the hypothesis of traffic composed of light vehicles only:

- *Scenario a*: The COM-Roundabout is configured as a Single-Lane Roundabout (single entry lane conflicted by one circulating lane). The equation for estimating the entry capacity is (HCM 7th Edition, 2022):

$$c_i = 1380e^{\left(-1.02 \cdot 10^{-3}\right) \cdot q_{c,i}} \tag{5}$$

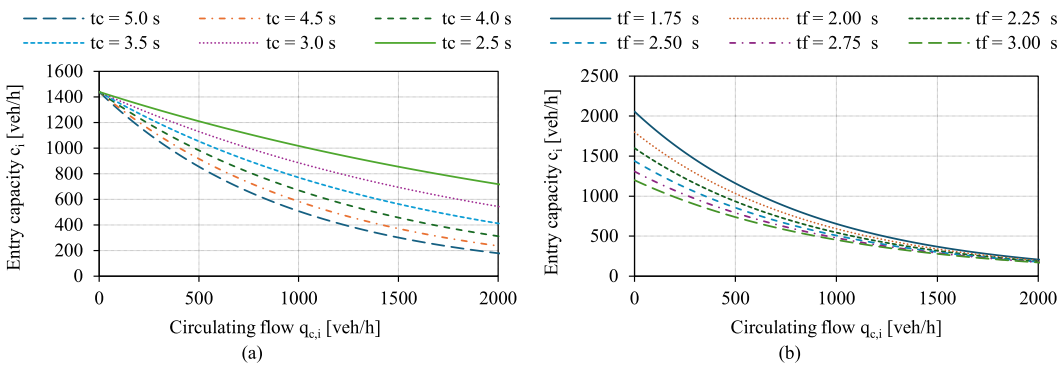

Fig. 3. Entry capacity variations as a function of circulating flow, critical gap and follow-up time. (a) t_f = 2.5 s and t_c = 2.5–5.0 s; (b) t_c = 5 s and t_f = 1.75–3.00 s.

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 b:* The COM-Roundabout is configured with Two-Lane Entries Conflicted by One Circulating Lane. The capacity of each entry lane conflicted by one circulating lane is (HCM 7th Edition, 2022):

$$c_i = 1420e^{(-0.91\cdot 10^{-3})\cdot q_{c,i}} \tag{6}$$

In which all variables are previously defined

- *Scenario c:* The COM-Roundabout is configured with One-Lane Entries Conflicted by Two Circulating Lanes. The capacity of each entry is (HCM 7th Edition, 2022):

$$c_i = 1420e^{(-0.85\cdot 10^{-3})\cdot q_{c,i}} \tag{7}$$

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

- *Scenario d:* The COM-Roundabout is configured with Two-Lane Entries Conflicted by Two Circulating Lanes. The capacity of the right and left lanes at entries are computed as follows (HCM 7th Edition, 2022):

$$c_{i,R} = 1420e^{(-0.85\cdot 10^{-3})\cdot q_{c,i}} \tag{8}$$

$$c_{i,L} = 1350e^{(-0.92\cdot 10^{-3})\cdot q_{c,i}} \tag{9}$$

where $c_{i,R}$ and $c_{i,l}$ are the capacity (veh/h) of the right and left entry lanes of the i-th arm respectively and $q_{c,i}$ is the total conflicting flow rate (veh/h) of both circulating lanes in front the i-th arm.

The entry capacity can be estimated using the following relationship:

$$c_i = \frac{c_{i,R} + c_{i,L}}{\max\left(\frac{q_{e,i,R}}{c_{i,R}}; \frac{q_{e,i,L}}{c_{i,L}}\right)} \tag{10}$$

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

Finally, when all the entry lanes of the COM-Roundabout are in unsaturated conditions, the total capacity C_{TOT} of the roundabout can be calculated with the relationship:

$$C_{TOT} = \sum_{i=1}^{N} c_i \tag{11}$$

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).

3.2. Delay, queue and LOS estimation

It is well known that when the entry flow reaches or exceeds entry capacity, significant delays, queues, and congestion can occur (Assolie et al., 2023). According to the HCM procedure (HCM 7th Edition, 2022), control delay and queue of each lane of a roundabout approach are estimated with the following relationships:

$$d = \frac{3600}{c} + 900\cdot T\cdot\left[x - 1 + \sqrt{(x-1)^2 + \frac{\frac{3600}{c}\cdot x}{450\cdot T}}\right] + 5\cdot\min[x,1] \tag{12}$$

where d is the average control delay of the entry lane under consideration (s/veh), x is the volume-to-capacity ratio (i.e. the ratio between the entry flow and the entry capacity) of the subject lane, c is the capacity of the subject lane (veh/h), and T is the time interval period.

The control delay d_i for the i-th approach with two lanes (right and left) is calculated by computing a weighted average of the delay for each lane on the approach, weighted by the volume in each lane, namely:

$$d_i = \frac{d_{e,i,R}\cdot q_{e,i,R} + d_{e,i,L}\cdot q_{e,i,L}}{q_{e,i,R} + q_{e,i,L}} \tag{13}$$

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 control delay for the entire intersection (d_{int}) is estimated as:

$$d_{int} = \frac{\sum_{i=1}^{N} d_i\cdot q_{e,i}}{\sum_{i=1}^{N} q_{e,i}} \tag{14}$$

in which $q_{e,i}$ is the entry flow from the i-th arm.

The level of service (LOS) is determined as summarized in Table 2.

The 95th percentile of queue Q for a given lane on an approach is calculated with the expression (HCM 7th Edition, 2022):

$$Q = 950 \cdot T \cdot \left[x - 1 + \sqrt{(x-1)^2 + \frac{\frac{3600}{c} \cdot x}{150 \cdot T}} \right] \cdot \left(\frac{c}{3600} \right) \tag{15}$$

where Q is the 95th percentile queue (veh), x is the volume-to-capacity ratio of the subject lane, c is the capacity of the subject lane (veh/h), and T is the analysis period (h) (T = 1 for a 1 – h analysis; T = 0.25 for a 15-min analysis).

3.3. Effect of CAVs

Due to the smaller acceptable gaps, the presence of CAVs in traffic streams can increase the roundabouts' capacity. The potential benefits in terms of capacity, delay, queue, and LOS increase more and more with the increase in the proportion of CAVs in traffic streams. This effect can be clearly appreciated by the model and adjustment factors for CAVs proposed by the Highway Capacity Manual 7th Edition (HCM 7th Edition, 2022). The general form of the entry capacity model in the presence of CAVs is (HCM 7th Edition, 2022):

$$c_i = f_A \cdot A \cdot e^{-f_B \cdot B \cdot q_{c,i}} \tag{16}$$

where c_i here denotes the entry lane capacity, adjusted for CAVs; A is the intercept parameter, B is the slope parameter, $q_{c,i}$ is the conflicting flow rate, f_A is the adjustment factor for the intercept parameter and f_B is the adjustment factor for the slope parameter.

Table 3 gives the values of A and B to consider the appropriate combination of the number of entry lanes and conflicting circulating lanes. The capacity adjustment factors for CAVs, obtained based on microsimulations, are given in Table 4.

Figs. 4–7 show four different operational scenarios of the COM-Roundabout, denoted as follows:

- Scenario *a* (the COM-Roundabout is configured as a single-lane roundabout, Fig. 4);
- Scenario *b* (the COM-Roundabout presents one-lane entry conflicted by two circulating lanes, Fig. 5);
- Scenario *c* (the COM-Roundabout presents two-lane entry conflicted by one circulating lane, Fig. 6);
- Scenario *d:* (the COM-Roundabout is configured as a two-lane entry conflicted by two circulation lanes, Fig. 7).

Each is characterized by an identical number of active lanes at the entries and on the ring on each arm. The inactive lanes are indicated in the VMS panels and identified on the road pavement by red LEDs. The entry capacity was determined by considering the layout (i.e., available entry and circulating lanes) and the proportion of CAVs in the traffic stream (from 0% to 100%). From Figs. 4–7, the number of lanes increases and, therefore, the entry capacity. In particular, considering a generic value of circulating flow ($q_{c,i}$ = 0 – 2000 veh/h) in front of each approach, the entry capacity significantly increases comparing Scenario d and Scenario a. Moreover, with the increase in the percentage of CAVs, the entry capacity increases, and this is because autonomous vehicles can complete the entry manoeuvre on the ring by exploiting smaller gaps in the circulating stream. However, it is quite clear that a considerable variation in capacity is obtained by comparing the single-lane roundabout scenario (Fig. 4) with the double-lane roundabout scenario (Fig. 7).

Fig. 8 shows that the percentage increase in the entry capacity of Scenario d, compared to Scenario a, grows more and more with the increase of the circulating flow, varying from a minimum of 92% to a maximum of 204% in relation to the proportion of CAVs in traffic streams.

4. Safety analysis models

Safety is the most important aspect when a new road or intersection is designed (Dinnella et al., 2020). This research estimated the expected number of accidents at COM-Roundabout by using the general models of the Research Report 888 (Ferguson et al., 2018). A predictive accident model involves a Safety Performance Function (SPF) and several Crash Modi-

Table 2
Level of Service (LOS) as a function of control delay.

Control delay [s/veh]	Level of Service (LOS)	
	x = volume/capacity ≤ 1	x = volume/capacity > 1
0 - 10	A	F
10 - 15	B	F
15 - 25	C	F
25 - 35	D	F
35 - 50	E	F
>50	F	F

Table 3
Roundabout Entry Lane Capacity Model Parameters (without CAVs).

Entry Lane Type	A	B
One-lane entry conflicted by one circulating lane	1,380	1.02×10^{-3}
Two-lane entry conflicted by one circulating lane (both entry lanes)	1,420	0.91×10^{-3}
One-lane entry conflicted by two circulating lanes	1,420	0.85×10^{-3}
Two-lane entry conflicting by two circulating lanes (right entry lane)	1,420	0.85×10^{-3}
Two-lane entry conflicting by two circulating lanes (left entry lane)	1,350	0.92×10^{-3}

Table 4
Capacity adjustment factors by penetration rate of CAVs for conventional roundabouts (HCM 7th Edition).

Proportion of CAVs in Traffic Stream	1-Lane Entry				2-Lane Entry					
	1 Circulating Lane		2 Circulating Lanes		1 Circulating Lane Both Lanes		2 Circulating Lanes Left Lane		2 Circulating Lanes, Right Lane	
Traffic Stream	f_A	f_B	f_A	f_B	f_A	f_B	f_A	f_B	f_A	f_B
0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
20	1.05	0.99	1.03	0.99	1.05	0.99	1.03	0.99	1.05	0.96
40	1.12	0.97	1.08	0.96	1.12	0.97	1.08	0.96	1.12	0.93
60	1.22	0.94	1.18	0.92	1.22	0.94	1.18	0.92	1.20	0.87
80	1.29	0.90	1.28	0.89	1.29	0.90	1.28	0.89	1.27	0.84
100	1.35	0.85	1.38	0.85	1.35	0.85	1.38	0.85	1.34	0.80

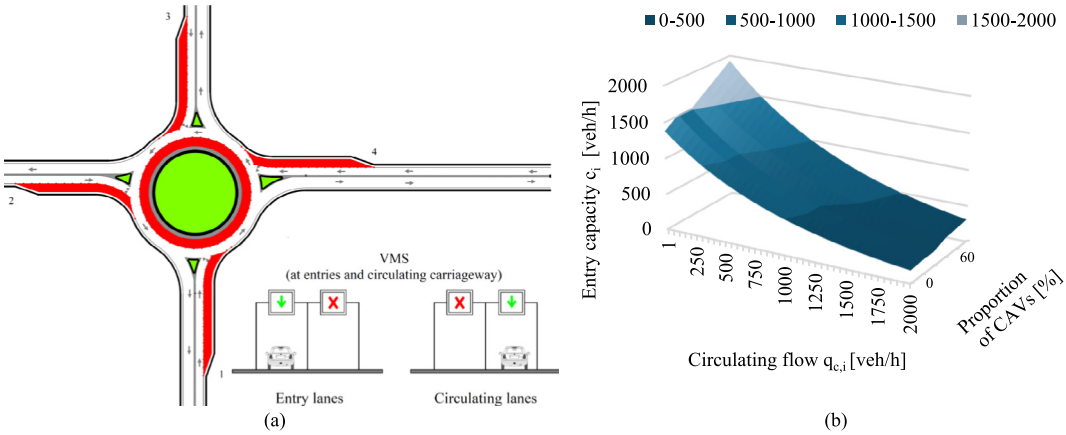

Fig. 4. Entry capacity variation as a function of circulating flow and different proportions of CAVs. *Scenario a* (One-lane entry conflicted by one circulating lane) – inactive lanes are marked in red.

fication Factors (CMFs). CMFs are multiplicative factors used to compute the change in road safety (i.e. crash risk) outcomes from implementing a single or combined treatment or for taking into consideration countermeasures and geometric and traffic characteristics different from those of basic conditions at a specific site.

The SPF is employed to assess the average crash frequency for a generic roundabout whose characteristics are consistent with the SPF's stated base conditions. Instead, the CMFs are applied to correct the SPF estimate when the analysed roundabout's properties are inconsistent with the base conditions. Finally, a local calibration factor C must be considered to modify the results of the predicted model with the real accident data when available. To compute the crash frequency, the equation is (Ferguson et al., 2018):

$$ACF = C \cdot N_{SPF} \cdot (CMF_1 \cdot CMF_2 \cdot \ldots \cdot CMF_n) \tag{17}$$

where ACF is the predicted average crash frequency (crashes/yr), C is the local calibration factor, N_{SPF} is the predicted average crash frequency for base conditions (crashes/yr); CMFi is the CMF for traffic characteristic, geometric element, or traffic control feature i (i = 1 to n), and n is the total number of CMFs.

The safety performance functions for single-lane roundabouts and multi-lane roundabouts are given by Eqs. (18) and (19) respectively.

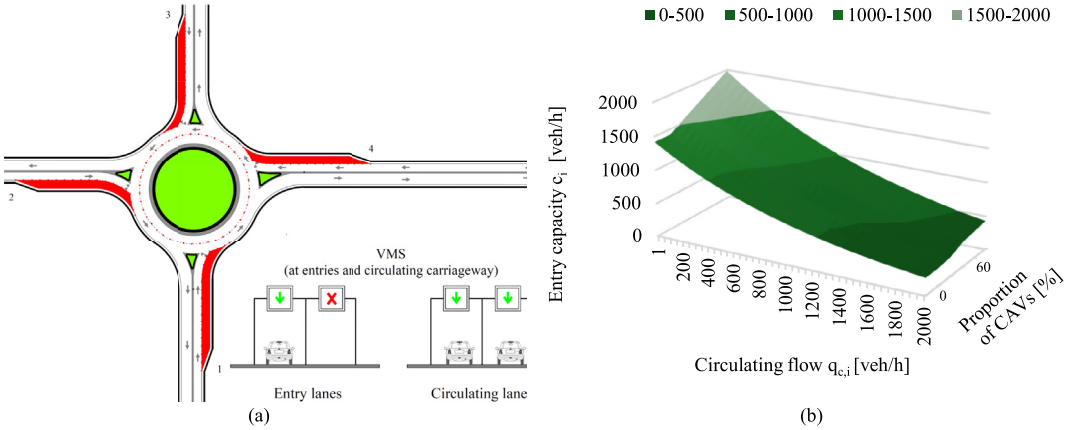

Fig. 5. Entry capacity variation as a function of circulating flow and different proportions of CAVs. *Scenario b* (One-lane entry conflicted by two circulating lanes) – inactive lanes are marked in red.

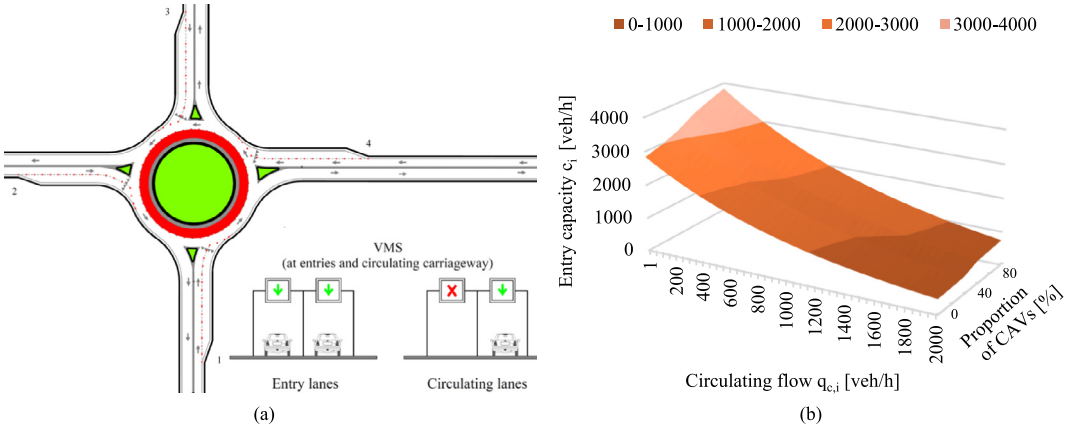

Fig. 6. Entry capacity variation as a function of circulating flow and different proportions of CAVs. c) *Scenario c* (two-lane entry conflicted by one circulating lane) – inactive lanes are marked in red.

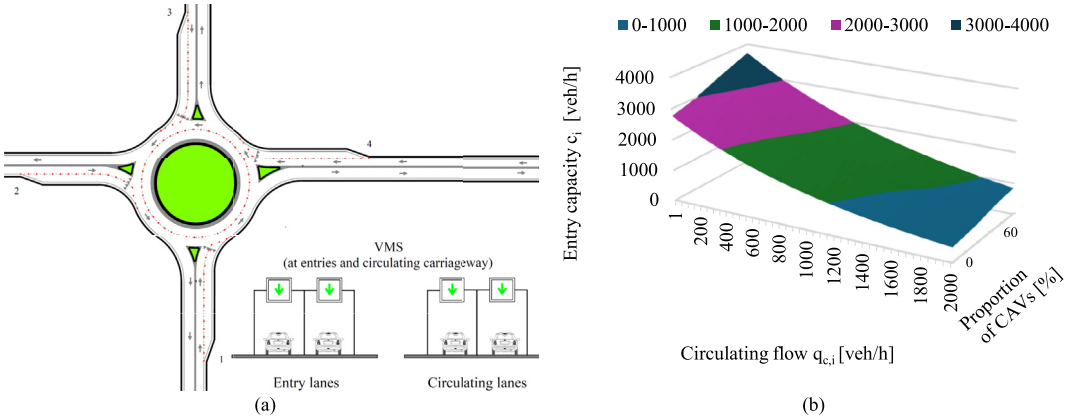

Fig. 7. Entry capacity variation as a function of circulating flow and different proportions of CAVs. *Scenario d* (two-lane entry conflicting by two circulating lanes) – inactive lanes are marked in red.

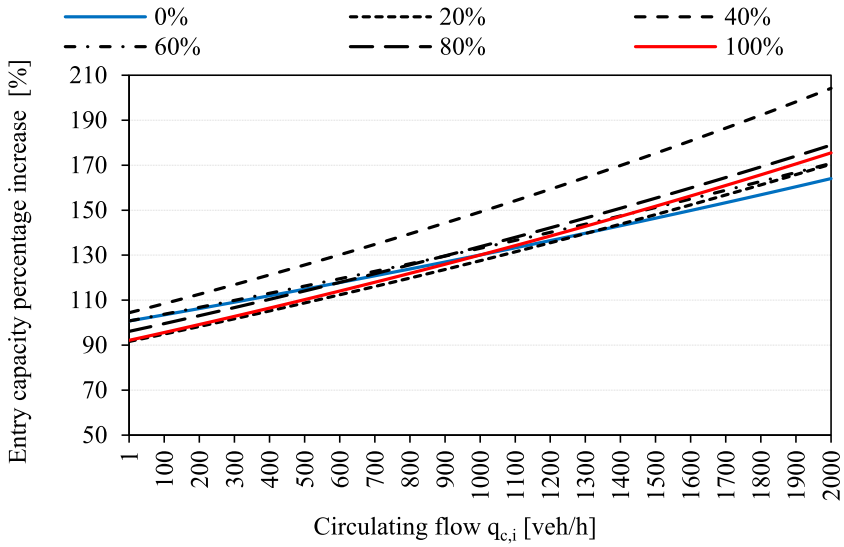

Fig. 8. Entry capacity percentage increase of the Scenario d compared to Scenario a, as a function of circulating flow and different proportions of CAVs.

$$N_{SPF} = \exp\left[-3.503 + 0.915 \cdot LN(EntAADT/1000) + 0.206 \cdot I_{rural}\right] \tag{18}$$

$$N_{SPF} = \exp\left[-3.535 + 1.276 \cdot LN(EntAADT/1000) + 0.250 \cdot I_{rural}\right] \tag{19}$$

where N_{SPF} is the predicted average crash frequency for base conditions on all legs (crashes/yr), the Ent AADT is the entering annual average daily traffic, I_{rural} is the area type indicator variable (=1.0 if the area is rural, 0.0 otherwise). The entering AADT indicates the sum of the AADT that enters the roundabout when considering all legs.

Considering the symmetrical layout of the COM-Roundabout, the entry width is the same as the base conditions (20 ft or 29 ft if only one or two entering lanes are activated in each approach, respectively), the essence of access points, bypass lanes, and that the analysed case is not assimilable to an interchange crossroad-ramp terminal roundabouts with one outbound-only leg only the CMF_{ICD} for the inscribed circle diameter are considered when the COM-Roundabout is configurated as a single-lane condition. The CMF_{ICD} equation is (Ferguson et al., 2018):

$$CMF_{ICD} = \exp\left[-0.00621(ICD - 125)\right] \tag{20}$$

where ICD is the inscribed circle diameter (ft), it is assumed to be 50 m (or 164 ft).

Considering that the COM-Roundabout is at the conceptual stage of development, no accident data are available from the real world to estimate the calibration factor C. Therefore, in this study, the value C = 1 was assigned for the estimation of the predicted average crash frequency.

5. Input data for performance and safety analysis

In this research, numerous traffic simulations were performed. We suppose that in all analysed traffic conditions, the circulation lanes and exit lanes are always in undersaturated conditions (x = ratio capacity/flow < 1). Consequently, the congestion phenomena may only depend on saturated or oversaturated entries. In addition, a transient state is not considered in this work. Considering the arms of Fig. 1, and the time instant t, the traffic demand can be expressed by the Origin-Destination matrix $M_{O/D}(t)$:

$$M_{O/D}(t) = \begin{vmatrix} Q_{1,1}(t) & Q_{1,2}(t) & Q_{1,3}(t) & Q_{1,4}(t) \\ Q_{2,1}(t) & Q_{2,2}(t) & Q_{2,3}(t) & Q_{2,4}(t) \\ Q_{3,1}(t) & Q_{3,2}(t) & Q_{3,3}(t) & Q_{3,4}(t) \\ Q_{4,1}(t) & Q_{4,2}(t) & Q_{4,3}(t) & Q_{4,4}(t) \end{vmatrix} \tag{21}$$

The Matrix (21) can also be expressed in the vector form:

$$M_{O/D}(t) = [Q_{ij}(t)], i, j = 1, 2, 3, 4. \tag{22}$$

where $Q_{ij}(t)$ is the traffic volume (veh/h) that enters from the generic arm "i" and exits from the generic arm "j" of the roundabout.

Many traffic conditions were analysed to determine the most comprehensive results possible. In total 1,000,000 $M_{O/D}(t)$ matrices were used to consider a wide range of combinations of traffic demand intensity and the percentage distribution of manoeuvres at COM-Roundabout. With the Origin-Destination matrices, entering, circulating and exit flows were computed, and capacity, delay, queue and LOS were estimated with the relationships summarized in Sect. 3.

For instance, considering Entry 1 for Scenario a (One-lane entry conflicted by one circulating lane, cf. Fig. 4), at the time t, the circulating flow is $q_{c,1}(t) = [Q_{2,4}(t) + Q_{2,3}(t) + Q_{2,2}(t)] + [Q_{3,4}(t) + Q_{3,3}(t)] + Q_{4,4}(t)$, instead the entry flow is $q_{e,1}(t) = [Q_{1,1}(t) + Q_{1,2}(t) + Q_{1,3}(t) + Q_{1,4}(t)]$. Then, entry capacity and control delay are computed from Eqs. (5) and (12), respectively.

Let's consider the generic Q_{ij} as the design hourly volume related to the traffic stream i-j. The following relationship among flows Q_{ij} and Annual Average Traffic $AADT_{ij}$ can be considered:

$$Q_{ij} = \alpha \cdot PHF \cdot AADT_{ij} \tag{23}$$

where α is the ratio between Q_{ij} and $AADT_{ij}$ (α = 0.08–0.10) obtained from statistical data and PHF is the Peak Hour Factor (PHF) that compares the traffic volume during the busiest 15-minutes of the peak hour with the total volume during the peak hour (PHF = 0.90–0.95 for urban roads with high traffic values).

In this research, it was set α = 0.10 and PHF = 0.90.

6. Results and discussion

As previously described, 1,000,000 Origin-Destination traffic matrices $M_{O/D}(t)$ were analysed to consider different entry flow values and traffic distributions among the COM-roundabout arms. For the sake of simplicity and synthesis, only the results regarding predicted accidents and MOEs for the COM-Roundabout related to Scenarios (a), (b), (c), and (d) (Figs. 4–7) are given.

According to Eqs. (17)–(19), the predicted crash frequency increases with the increase of the total AADT. The traffic rule that offers higher safety is Scenario a in which the traffic control system is assimilable to a single-lane roundabout. At the same time, this Scenario generates lower entry and total capacity than the others. As it is clear from Figs. 9–13, as the number of activated lanes increases, the COM-Roundabout's performance improves (in terms of capacity, delay, LOS, and queue); however, this comes at the cost of reduced safety. Among the analysed traffic rules, the two very different traffic control systems can be identified and analysed:

- Scenario *a* (the COM-Roundabout is configured as a Single-Lane Roundabout): high safety, low capacity;
- *Scenario d:* (the COM-Roundabout is configured as a Double--lane Roundabout): high capacity, low safety.

Fig. 9 shows some results of the safety analysis. Fig. 9a shows that in the Scenario a, accidents increase almost linearly with increasing Entry AADT and therefore mean delay, while sustaining low crash rates below 1 crash/year. This further indicates that Scenario a is suitable for very low to moderate inflows. Contrasted with that, the Scenario d (Fig. 9b) follows an increase in crashes up to a maximum of 4 crashes/year. Therefore, Scenario d is associated with greater crash risks.

Fig. 10 gives the relationship developed between Entry AADT and Crash Frequency. In Scenario a (Fig. 10 a), the relationship observed exhibits linear relations where crash frequency gradually goes upwards beyond 15,000 veh/day of Entry AADT. This underlines the safety advantages of Scenario a for traffic flow conditions in the low and middle range. In contrast, Scenario d (Fig. 10b) shows a more rapid increase in the frequency of crashes as the total inflow increases, which underlines the increased dangers of double-lane layouts, especially when significant volumes of traffic are expected.

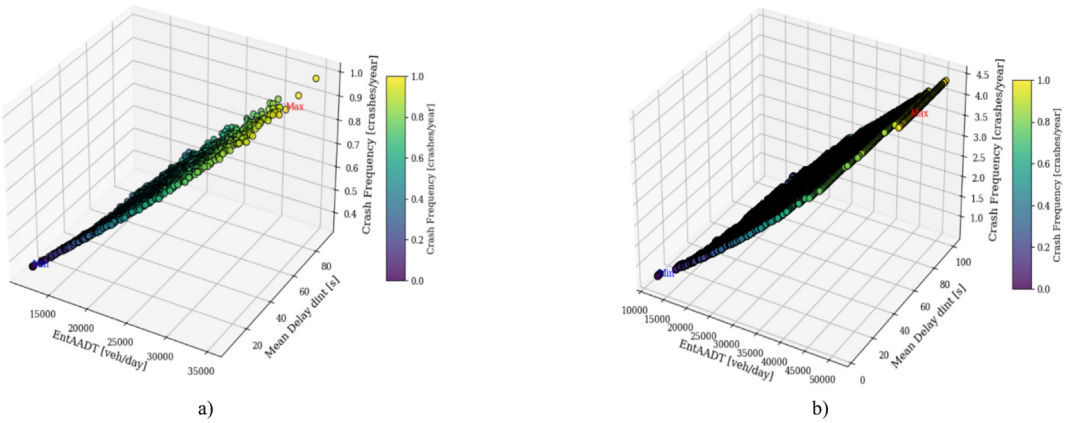

Fig. 9. Relation among expected crash frequency, Entry AADT and mean delay. (a) Scenario a (the COM-Roundabout is configured as a Single-Lane Roundabout); (b) Scenario b (the COM-Roundabout is configured as a Double–lane Roundabout).

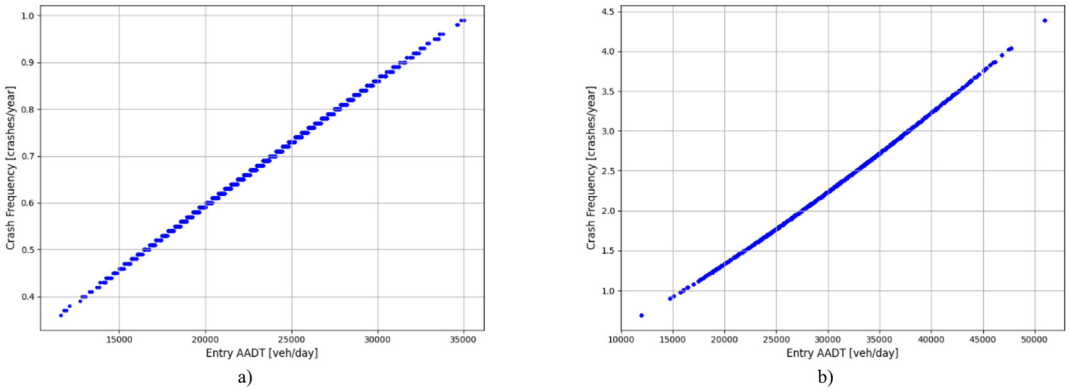

Fig. 10. Relation between expected crash frequency and Entry AADT. a) Scenario a (the COM-Roundabout is configured as a Single-Lane Roundabout); (b) Scenario b) (the COM-Roundabout is configured as a Double–lane Roundabout).

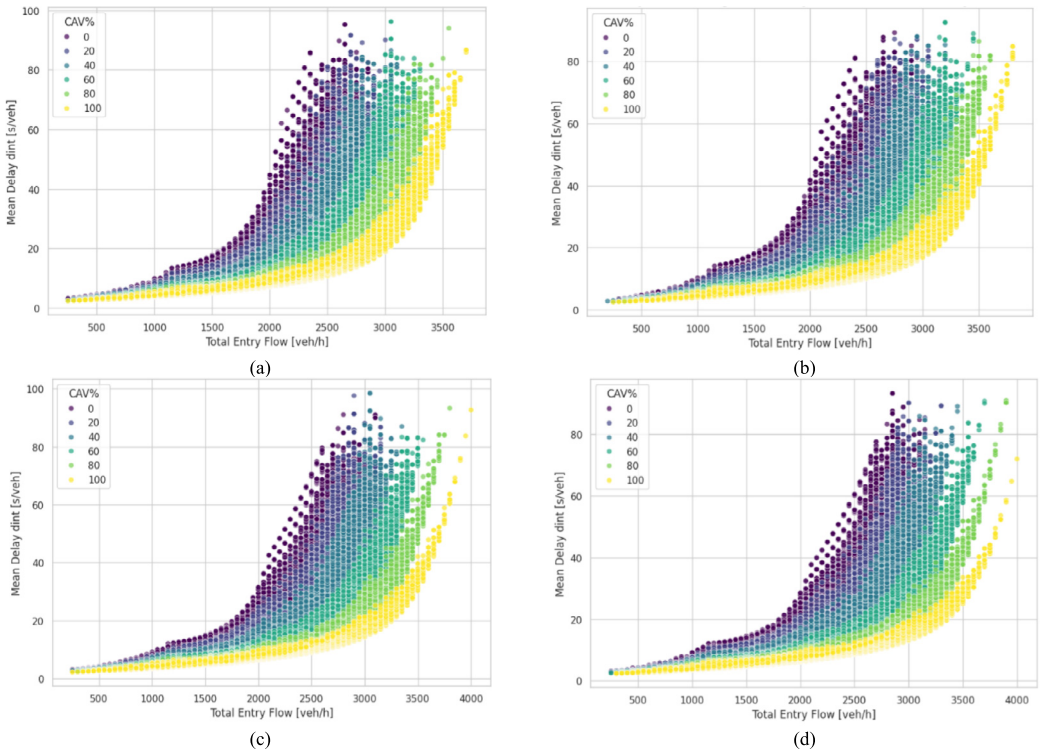

Fig. 11. COM-Roundabout mean delay as a function of total inflow for different CAV percentage. (a) Scenario a; (b) Scenario b; (c) Scenario c; (d) Scenario d.

The remaining scenarios (i.e. Scenario b and Scenario c) summarized in Table 1 offer intermediate safety and capacity levels compared to Scenarios *a* and *d*.

Therefore, the COM-Roundabout combines the benefits of different roundabouts by switching its configuration and the traffic rules according to changing traffic needs. By modulating the traffic rules (i.e. by appropriately activating/deactivating the lanes at the entries and on the circulating carriageway of the Scenarios in Table 1), it is possible to modify the capacity as a function of the traffic demand at time t (i.e. of the $M_{O/D}(t)$ measured by the vehicle counting systems) and at the same time the safety of the roundabout. Unlike traditional roundabouts, the COM-Roundabout allows for the optimization of capacity and safety. For example, the number of active lanes at the entries and on the ring can be reduced during night hours since the traffic demand is low. The resulting reduced capacity can be sufficient to handle the incoming traffic flows, and the safety offered is the maximum possible. When traffic demand increases, more lanes can be activated until – if necessary – Scenario *d* is reached. This Scenario can be kept active until the traffic demand decreases. Consequently, switching to a different scenario is possible, decreasing the COM-Roundabout's capacity but increasing safety simultaneously.

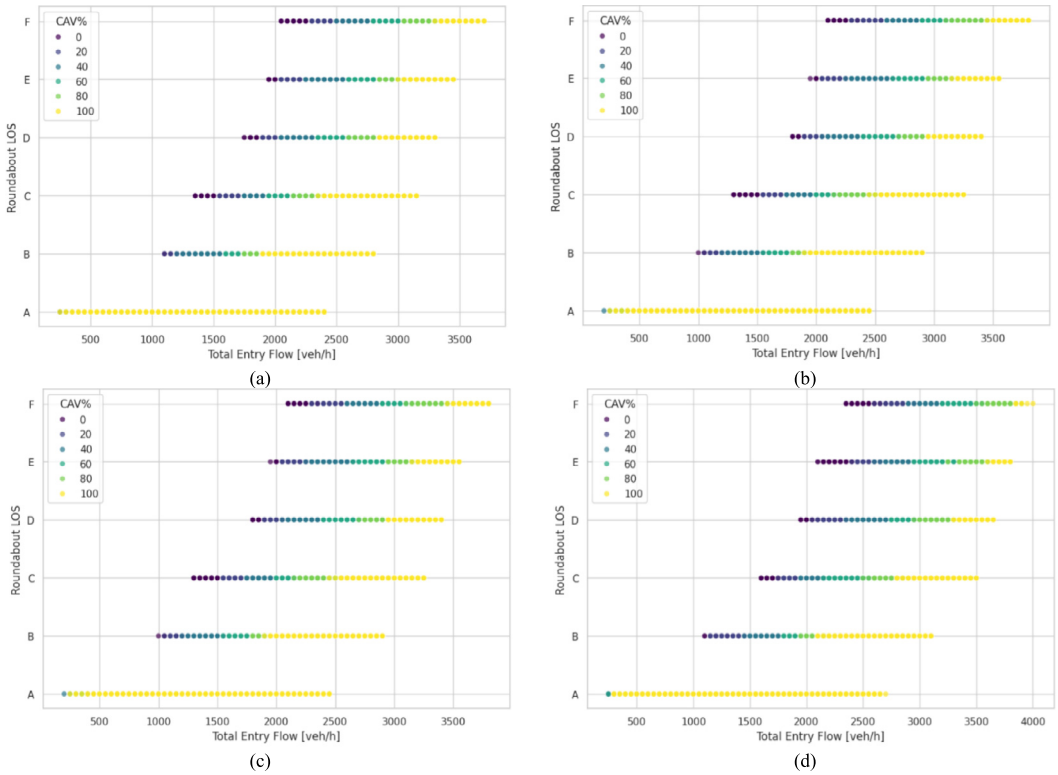

Fig. 12. COM-Roundabout LOS as a function of total inflow for different CAV percentages. (a) Scenario a; (b) Scenario b; (c) Scenario c; (d) Scenario d.

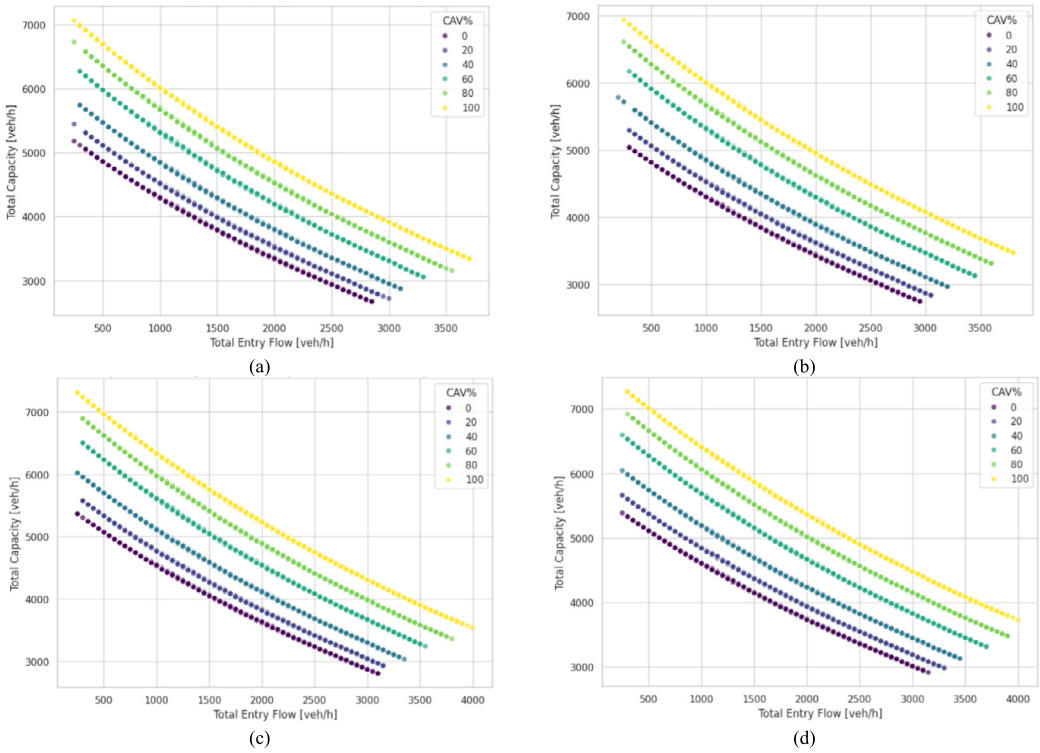

Fig. 13. COM-Roundabout Total Capacity as a function of total inflow for different CAV percentages. (a) Scenario a; (b) Scenario b; (c) Scenario c; (d) Scenario d.

To investigate the simultaneous effect of the traffic regulation type and the influence of CAVs on the operation of the COM-Roundabout, additional Origin-Destination traffic matrices were considered. All conditions included a total vehicle entry flow ranging between 50 and 1000 veh/h per entry and Connected and Autonomous Vehicles (CAVs) comprised anywhere from 0% (only manual vehicles) to 100% (fully autonomous traffic). In the case of Scenario d (2 entry lanes and 2 circulating lanes), all entry lanes are assumed to be equally utilized at 50% ($q_{e,i,R} = q_{e,i,L}$). Also, the percentage distribution among exits was assumed in the proportion 1/3, 1/3 and 1/3.

Fig. 12 presents the Level of Service (LOS) versus the total entry flow for the various scenarios and for different percentages of CAVs. LOS ranges from A (excellent performance) to F (saturation and congestion). The results showed a very consistent pattern of how high percentages of CAVs greatly improved the roundabout LOS at all entry flow levels. For 100% CAVs conditions, the LOS remains favorable (A–C) at increasing entry flow, while for lower penetration rates, such as close to 0%, the degradation in LOS is faster, especially at higher entry flows. Scenario a and Scenario b (Single-lane entry configurations) show a more rapid decrease in LOS with the increased flow than Scenario c and Scenario d (two-lane entries) reflecting their lower capacity and inability to handle higher traffic volumes. Comparing scenarios with equal entry lanes but different numbers of circulating lanes, it is felt that two circulating lanes normally maintain a better LOS within all entry flow levels. In scenarios where entry lanes differ but the circulating lanes are similar, two-lane entries always present a better LOS (A–C) at higher traffic flows than single-lane entries. Single-lane entries degrade in LOS much faster, especially at higher entry flows, because of their limited capacity.

Fig. 11 shows the relationship between the mean delay of the intersection (Eq. (14) and total entry flow for Scenarios a, b, c, and d, considering varying levels of Connected and Autonomous Vehicles (CAVs) penetration. It is clearly evident that with the increase in the presence of CAVs, regardless of the type of scenario, the amount of delay decreases significantly. However, the use of CAVs appears to lessen the mean delays more in the higher traffic volume scenarios than in the lower care due to fewer conflicts that arise. The trend is noted to hold true on all the configurations, highlighting the advantages of CAV's proportion increases. The scenarios with two entry lanes are more effective than those with single entry lane because they recorded lower mean delays.

Fig. 13 shows the Total Capacity (C_{TOT}) in Scenarios a, b, c and d, for different penetration of CAVs (0%-100%). The results show that configurations with two circulating lanes have higher capacities than one circulating lane configurations, making them more efficient. Similarly, two-lane entry configurations show significantly higher capacities than single-lane entry configurations since the extra entry lane increases throughput and better accommodates traffic demand. In general, total capacity improvements are evident with the increased presence of CAVs and were highest in cases involving 100% CAVs, showing that, indeed, automation holds the possibility for improvement in the COM-Roundabout performance. Again, the capacity analysis underlines the benefits of automation: the highest capacities of each configuration are found for 100% CAVs penetration, demonstrating the ability of CAVs to satisfy higher traffic demand. These findings underline the need to incorporate CAV-friendly infrastructure and design features.

To clarify how it was previously explained in terms of self-regulation procedures, consider this very simple case study (Fig. 14) regarding the LOS evaluation of two traditional intersections: single and double-lane roundabouts. The AADT = 35,520 veh/day and total inflow vary during the 24 h of a day, with a minimum and a maximum hourly total inflow of 120 veh/h and 2770 veh/h (only human-driven vehicles), respectively, with a constant distribution of traffic during the days of each year. The flow is equally distributed among the 4 arms ($Q_{e1} = Q_{e2} = Q_{e3} = Q_{e4}$), and the percentage distribution of left-turn, right-turn and straight manoeuvre is in the proportion 1/3, 1/3, 1/3. With such traffic distributions, the LOS of the single-lane roundabouts ranges from LOS A to LOS F (Fig. 14a); instead, the LOS of the double-lane roundabouts is constantly LOS A except for one hour during the day in which the LOS is B (Fig. 14b). Therefore, from the capacity performance perspective, the best solution is the double-lane roundabout. However, by applying Eqs. (1)–(19), we obtain that the predicted acci-

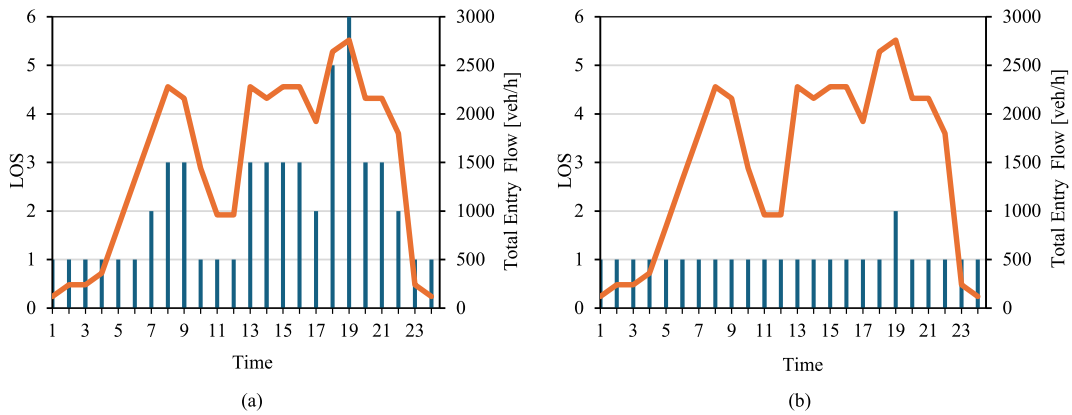

Fig. 14. LOS comparison. (a) Conventional Single-lane Roundabout. (b) Conventional Double-lane Roundabout. (1 = LOS A, 2 = LOS B; 3 = LOS C, 4 = LOS D, 5 = LOS E, 6 = LOS F).

dents for the single-lane roundabout and the double-lane roundabout are 0.62 accidents/year and 2.77 accidents/year, respectively. Therefore, the double-lane roundabout generates an accident increase of 357% compared to the single-lane roundabout. Now consider a COM-Roundabout under the same traffic conditions. In this case, different lane activation programs can be foreseen (Fig. 15). For example, the road operator chooses to guarantee during the day a level of service at least equal to LOS C (Control Program 1). Then, the controller (Fig. 2) indicates the following configurations:

- Scenario *a*: from 0:00 to 18:00 and from 20:00 to 24:00;
- Scenario *b*: from 18:00 to 20:00;

The Scenario b only lasts two hours in the day and in the COM-Roundabout, two entry lanes and two circulating lanes are activated. In this case, the predicted accident rate is 0.90 accidents/year. Instead, if the minimum desirable LOS is B, the controller (Fig. 2) must indicate the following configurations (Control program 2):

- Scenario *a*: from 0:00 to 8:00, from 09:00 to 13:00, from 17:00 to 18:00, from 22:00 to 24:00;
- Scenario *b*: from 08:00 to 10: 00, from 13:00 to 17: 00, from 13:00 to 17:00, from 18:00 to 22:00.

Hence, Scenario a and b are activated for 14 and 10 h during the day, respectively, with a consequent slight increase in expected accidents per year.

This brief example demonstrates how it is possible to modulate and control the COM-Roundabout according to the intensity of traffic demand ($M_{O/D}(t)$) and the desired LOS and safety.

Therefore, the COM-Roundabout can be considered as an adaptive smart roundabout, able to switch its technical characteristics depending on the Origin-Destination traffic matrix, the layout scenario (activation of lanes at the entries and on the circulating carriageway, cf. Table 1), the desired LOS and safety level. Furthermore, in the future, the traffic programming system could be coordinated with CAVs (Danesh et al., 2021), further amplifying the COM-Roundabout benefits.

7. Conclusions

The research presents a new concept of self-regulating roundabout: the COM-Roundabout (Commutable Roundabout). Thanks to vehicle and queue detectors, smart cameras, LED road markers, and Variable Message Signs (VMS), vehicles are channelled into one or two entry lanes and in one or two circulating lanes, depending on the current intensity and distribution of traffic flows. Then, several layout scenarios were considered for the COM-Roundabout, from a minimum configuration comparable to a single-lane roundabout to a maximum configuration similar to a double-lane roundabout. From this perspective, the COM-Roundabout brings together the benefits of different roundabouts by switching its configuration over time, depending on the traffic variations. The COM-Roundabout traffic performance improves (in terms of capacity, delay, LOS and queue) as the number of activated lanes increases. Still, at the same time, the accident rates may rise.

Consequently, switching from one scenario to another can optimise both LOS and safety. The measures of effectiveness were evaluated in several traffic conditions considering one million $M_{O/D}$ traffic matrices and both HDVs and CAVs vehicles. The HCM and HSM models were applied. This research demonstrates that the COM-Roundabout could soon be used to optimise traffic performance (e.g. capacity and LOS) and safety thanks to its innovative features.

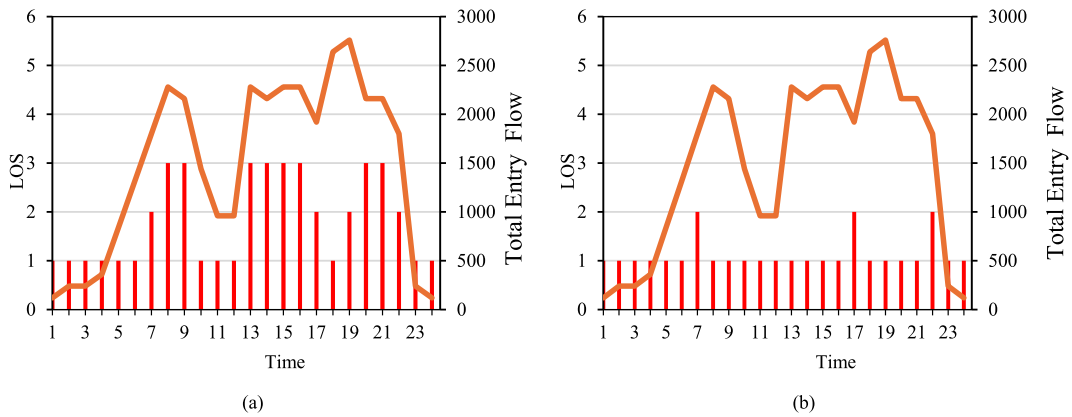

Fig. 15. LOS of the COM-Roundabout. (a) Control Program 1 (the worst admissible LOS is C). (b) Control Program 2 (the worst admissible LOS is B). 1 = LOS A, 2 = LOS B; 3 = LOS C, 4 = LOS D, 5 = LOS E, 6 = LOS F).

7.1. Major findings of the research

The model adopted in this research shows that CAVs will increase the performance of the COM roundabout in each possible scenario. For instance, if the proportion of CAVs in traffic streams is 100%, the LOS remains favourable (LOS A–LOS C) even at high traffic demand levels, while for lower penetration rates, degradation in LOS is faster. Scenarios with single-lane entry configurations exhibit a more rapid reduction in LOS with increases in traffic flows than scenarios with two active entry lanes. From a safety point of view, scenarios with only one circulating lane and one entry lane for each arm show advantages in the case of traffic flow levels in the low and middle range. On the other hand, the scenario with the activation of two circulating lanes and two entry lanes for each arm shows a more rapid increase in the predicted crash frequency as the total inflow increases, which demonstrates the increased accident risk of double-lane layouts, particularly in the case of high traffic flows.

Therefore, the self-regulating control mode and the correlated geometric layout allow for adapting COM-Roundabout's entry and total capacities to the traffic demand levels. Then, the COM-Roundabout's flexibility and traffic control system can optimize road safety and traffic efficiency.

Finally, in the future, the potential use of traffic manager control systems along with automation will create the best environment to indicate the CAV trajectories according to the activated lanes at a certain instant of time, further increasing the benefits of the proposed new roundabout type.

7.2. Limitations of the study

This research has its own limitations, which are encountered at various stages. The major limitation is that the COM-Roundabout is in the conceptual development stage; therefore, only closed-form capacity models used in conventional roundabouts were applied. In addition, it was considered the effect of only light vehicles. Finally, neither transient traffic states nor stochastic models of drivers were considered.

7.3. Research perspectives

Despite the promising findings, additional analyses are required (for instance, with the implementation of microscopic traffic models) to establish more accurate traffic programmes to establish a better procedure to optimise the safety and capacity of COM-Roundabout, even considering the transient effect of queue length. In addition, future research could explore additional layout scenarios, the impact of different percentages of heavy vehicles and the communication effect of a Traffic Manager System at roundabouts along with CAVs.

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.

CRediT authorship contribution statement

Marco Guerrieri: Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Masoud Khanmohamadi:** Writing – original draft, Visualization, Validation, Software, Investigation.

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