# Roundabouts: Traffic Simulations of Connected and Automated Vehicles—A State of the Art

Elena Campi, Gianpiero Mastinu, Giorgio Previati, Luca Studer, *Member, IEEE*, and Lorenzo Uccello

***Abstract*— The paper deals with traffic simulation within roundabouts when both "connected and automated vehicles" (CAVs) and human-driven cars are present. The aim is to present the past, current and future research on CAVs running into roundabouts within the Cooperative, Connected and Automated Mobility (CCAM) framework. Both microscopic traffic simulations and virtual reality simulations by dynamic driving simulators will be considered. The paper is divided into five parts. At first, the literature is analysed using the Systematic Literature Review (SLR) methodology based on Scopus database. Secondly, the influence of CAVs on roundabout-specific design features and configuration is analysed. Gap-acceptance models used to define the capacity of the roundabout, one of its most important key performance indicators, are also presented. Third, the most common simulation software are described and analysed in terms of traffic demand implementation. Then the communication approaches and path management algorithms are studied. An example is proposed on the integration of microscopic traffic simulations and dynamic driving simulators virtual reality simulations. Finally, car following models suitable for roundabout traffic are discussed. There is still a gap between simulations and actual experience. There are reasonable doubts on how modelling and optimizing CAVs' behaviour into roundabouts in view of CCAM. It seems that Cooperative, Connected and Automated Vehicles (CCAVs), more than simply Connected and Automated Vehicles (CAVs), could optimise traffic flow, safety and driving comfort within the roundabout. A very promising technology for traffic simulation within the roundabout seems the one based on dynamic driving simulators.**

***Index Terms*— Roundabout traffic simulations, cooperative, connected and automated vehicles, cooperative, connected and automated mobility, communication algorithms, car-following models, driving simulators.**

## I. INTRODUCTION

MANAGING road intersections have always been a challenging task because they constitute bottlenecks in the road network. Their poor management can produce road congestion and increase travel time, emissions and fuel consumption [1]. Moreover, inefficient management can produce risky situations for road users and can lead to accidents causing deaths and injuries [2]. In this scenario, introducing Connected and Automated Vehicles (CAVs) could lead to many advantages. Even more benefits are expected from Cooperative, Connected and Automated Vehicles (CCAVs) following the Cooperative, Connected and Automated Mobility (CCAM) paradigms [3].

The main objective of this paper is to provide an overview of how nowadays it is possible to model and simulate traffic scenarios which involve the presence of Cooperative, Connected and Automated Vehicles in roundabouts.

The topic is treated as comprehensively as possible, dealing with the simulation of traffic, its system performance, the dynamics of individual vehicles and their interaction with the environment. As stated in [4], in order to describe a specific traffic scenario, two types of simulation tools can be used:

- Microscopic Traffic Simulation (MTS), to obtain the traffic network performance.
- Dynamic Driving Simulator (DDS), to investigate individual human behaviour, driving comfort and safety.

MTS will be considered by describing the specific characteristics of traffic control mechanisms, such as roundabouts or traffic signals. Examples of traffic path management are presented using algorithms of various kinds, always considering the presence of CAVs or CCAVs in the network. Furthermore, the different car-following models that can be used to describe the behaviour of vehicles are described. Previous work [5], [6], has tried to integrate MTS and DDS virtual reality simulations by developing multi-participant simulations. This paper also aims to provide a comprehensive description of MTS and DDS virtual reality simulations so as to facilitate fully-fledged simulation platforms.

As stated in [7], for intersections "there are 3 main typical control mechanisms used almost anywhere in the world: *traffic signals*, [traffic lights] *stop signs* [give way/stops] and *roundabouts*".

- *Traffic signals* are efficient for intersections with heavy traffic
- *Stop signs* are suitable for intersections in which the traffic is light and unbalanced
- *Roundabouts* are an appropriate choice in case of moderate traffic with balanced flow from all the directions

Traffic signals and stop signs have been the first control mechanisms adopted to orchestrate road intersections [8]. Considering traffic signals, as stated in [9], the main problem is the signal timing control linked to the randomness of vehicular arrivals, the various intersection configurations, the vehicle types and the specific priorities considered in traffic management strategies. Furthermore, the advent of automated

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Manuscript received 24 March 2023; revised 2 August 2023; accepted 4 October 2023. This work was supported by the European Union's Horizon 2020 Research and Innovation Program under Grant 101015922. The Associate Editor for this article was A. Y. Lam. *(Corresponding author: Gianpiero Mastinu.)*

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Digital Object Identifier 10.1109/TITS.2023.3325000

and connected vehicles adds another layer of complexity to the network, having to consider also the possibility of communicating directly with the infrastructure and thus changing traffic light control logic [10]. Stop signs are simpler since they need no control algorithm and have been considered a valid alternative to traffic signals. In [11] Authors propose a study on the effect of stop signs considering road users' safety when converting a minor-approach-only stop (MAS) intersection to an all-way stop (AWS). Yielding rates have significantly increased from 45.7% to 76.7% and the minimum speed in the major approaches was reduced by 60.0%, leading to a safer, but slower intersection. Authors in [12] present an example of traffic signal replacement with stop signs in North America. All-way stop intersections proved to be safer with an overall reduction in crashes of 24% for both day and night. In all of the papers cited before [9], [10], [11], [12], the problem of maximising both efficiency and safety appears to be a common feature, also considering roundabouts. The same criticality still occurs whether AVs are present or not. This paper will deal with this conflicting performance problem.

More broadly, traffic signals and stop signs must be carefully considered with respect to the specific intersection properties and the objective of the management action, emphasizing increased safety, especially in low visibility conditions, and reduced traffic fluidity for all-way stops.

Since 1960 [13], roundabouts have garnered considerable attention in the field of transportation due to their exceptional capacity to enhance road safety. Authors in [14] reported, when converting high-speed rural roads to roundabouts, 52% and 67% reductions in total crashes and crash rate, respectively. Additionally, an 84% reduction in injury crashes and an 89% reduction in the injury crash rate. Roundabouts have the advantage of being designed to minimize conflict points, which is one of the biggest advantages they have over traditional signalized intersections, as shown in Fig. 1. It is well known that they feature a circular layout that ensures traffic moves in a unidirectional manner, significantly reducing the potential for accidents.

In addition, roundabouts eliminate left-turns (for countries with right-hand drive), in which vehicles turn left while crossing oncoming traffic, which are often associated with an increased risk of accidents, particularly head-on collisions. In roundabouts, it is rather complex to orchestrate CAVs. Consequently, traffic flow, safety and driving comfort have to be fully reconsidered. Authors in [14] deeply analyse crashes within roundabouts, highlighting a reduction in angle, head-on, and rear-end crashes. Nevertheless, sideswipe crashes and single-vehicle fixed-object collisions increase significantly [15]. Furthermore, the inherent safety benefits of roundabouts extend beyond their immediate impact on traffic. With a focus on reducing conflicts and enhancing the overall flow of vehicles, roundabouts can improve the overall efficiency and capacity of road networks with conventional vehicles. In [16] Authors conclude that roundabouts provide increased capacities compared to signal-controlled intersections when traffic volume is not heavy. In stark contrast to traditional intersections, roundabouts offer a unique approach to facilitating the smooth flow of traffic. By eliminating the need for drivers to come to a complete stop, roundabouts provide a seamless and efficient passage for vehicles. Authors in [17] proved the ability of roundabouts to reduce the vehicles' delay time when the traffic is not too severe, generating inbound queues that are too long. Roundabouts can also minimise the time spent at the intersection, helping to reduce congestion and promote smoother traffic movement, leading to a more sustainable and economical transportation system. In [18] Authors present the result of vehicles' emissions analysis in signalised and four-way-stop intersections and roundabouts, denoting a general reduction in $CO$, $CO_2$ and $NO_x$, up to 65%. It is crucial to highlight that these results are highly dependent on the driver's behaviour. The same study shows that considering aggressive drivers, the advantage of roundabouts in pollutant emission tends to decrease significantly.

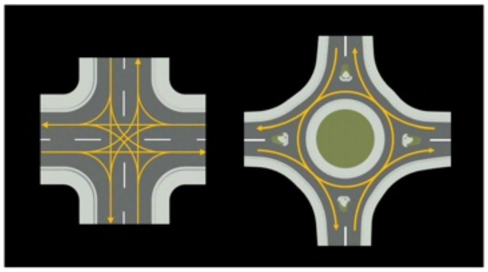

Fig. 1. Conflict points at four-leg intersection and single-lane roundabout [22].

It is worth noting that while the advantages of roundabouts are numerous, their successful implementation requires careful planning and consideration of various factors, including traffic volume, geometry, and pedestrian and cyclist accommodation. Authors in [19] show that the most frequent category of crash contributory factors was geometric design, which led to almost 60% of the total crashes analysed. For this reason, design practises must be properly defined leading to the creation of clear regulations. In [20], Authors propose a critical review of the regulations defining geometry design practices, guidelines and standards. Finally, inconsistencies, design errors and wrong requirements make the standard not able to achieve some of the main design objectives, such as optimal speed control.

The presence of CAVs makes it possible to optimize these characteristics of roundabouts, thus being able to achieve an even safer intersection, characterized by smoother traffic flow [21] and even lower fuel consumption.

Anyway, adopting the rules generally used to approach the roundabout, when traffic flow increases, congestion and conflicts are almost inevitable. This state-of-the-art paper presents a number of researches that aim to discover whether connected and automated vehicles (CAVs) might contribute to improve roundabout performance. CCAM is just addressed as the topic is very new and no sufficient contributions could be reviewed for our state-of-the-art paper. CAVs have the possibility to be aware of the traffic environment in real-time and to analyse it [23], share their motion states, the surrounding traffic conditions, their intentions and the behaviour they are planning to adopt. They could also be trained to pursue a cooperative objective, such as global fuel saving, which is studied for example in [24] in the case of truck platooning.

Recently, a state-of-the-art paper has been produced on the impact of connected and automated vehicles on road safety and efficiency [25]. In the paper, a need for the assessment of the impacts of CAVs on capacity using V2X communications at the network level was expressed, considering different traffic scenarios like roundabouts. In [26] this topic has been investigated, but the Authors assumed perfect communication between automated vehicles, without any noise or disturbances, leading to results that are only partially reliable. Another research [27] proposes platooning as a solution to improve the capacity of road infrastructure. In that case, the positive effect of this strategy could be appreciated only for medium and high market penetration rates of CAVs. In [28] the importance of the connection between vehicles is analysed. The Authors found out that the use of vehicles which are automated but not connected leads to an increase both in travel time and in delay for the same road network.

For these reasons, it is important to define and investigate the behaviour of the connected and automated vehicles while approaching, running into and exiting the roundabout.

At present, the roundabout constitutes an insurmountable obstacle for CAVs and CCAVs. In fact, in order to successfully cross a roundabout, it is fundamental to choose the correct entry and exit lane, and to understand how to follow priority rules, how to *interpret the intentions of other drivers* and how to deal with the existing traffic [29]. An ideal automated vehicle should be driven by a system that behaves how a human driver would, and in particular, should be able to understand other drivers' intentions under different driving circumstances and correct its actions according to the situations faced from time to time [30]. The most critical aspects of roundabout manoeuvres are related to interactions with other vehicles and to the perception of the surrounding environment. In particular, decisions must be made based on the movements of other interacting actors, which are dynamically changing according to the variations of the conditions of the driving scenario [31]. Moreover, as the values of the contributing factors vary, their impact on the situation changes. For instance, in [32] it is observed that when the relative longitudinal velocity between the considered vehicle and the surrounding ones increases, its effect on decisions decreases and relative distance becomes more significant. In addition to these considerations, navigation at roundabouts is often considered as either a problem of collision avoidance or a matter of efficient driving, but for automated vehicles to be accepted for replacing human drivers, the problem has to consider three objectives, all at once: safety, traffic flow and driving comfort. From this point of view, learning from human driving has shown promising results [33].

The paper addresses the problems introduced so far and it is organized as follows. At first, a systematic literature review is proposed to understand the extent of the field of study, its interest in the literature and any remaining gaps. Secondly, the roundabout configuration is introduced and available gap-acceptance models to obtain the roundabout capacity are presented. Then, the communication approaches and path management algorithms are discussed. Finally, car following models are analysed.

## II. SYSTEMATIC LITERATURE REVIEW

Bearing into consideration the main purpose of this research work, it is necessary to use a systematic methodology for the retrieval and analysis of available literature. In this regard, the Systematic Literature Review approach is considered. This method, as indicated in [25], considers a specific protocol in order to transparently review and present the relevant documentation. In such a manner, it is intended not only to summarize the existing evidence but also to highlight possible gaps in current research, thus being able to suggest areas for future studies. The SRL main steps to be addressed are [34]:

- A planning stage to address the research questions and develop the review protocol.
- A conducting stage to generate a search strategy and a specific search string used to obtain its results.
- A final reporting stage to communicate the results of the review proposed.

### A. SLR Methodology

Initially, the research questions are made explicit considering the basic objectives defined. Next, it is created the search string necessary for obtaining the documentation that will then be analyzed. Specific filters are considered in order to optimize the search and obtain results consistent with the search questions as much as possible. Once the final list of articles is obtained, they are analyzed, considering the countries of origin, years of publication, keywords used by the Authors, and the source of the articles in terms of publishers and individual journals. The proposed analysis aims to verify the validity of the research field and its evolution over the years, in terms of articles produced and consequently funds dedicated to the development of this technology. Beyond that, being able to consider keywords and their interconnectedness, SLR aims to investigate major themes and possible thematic clusters.

### B. Research Questions

Considering the objectives of this research work, the following key research questions are considered to develop the SLR:

- RQ1: Which are the available solutions to correctly simulate a traffic scenario in the presence of Cooperative, Connected and Automated Vehicles?
- RQ2: Can CAVs or CCAVs contribute to improve the traffic network performance and, more specifically, those related to intersections such as roundabouts?
- RQ3: What are the algorithms that can be used to manage CAVs or CCAVs within the roundabout and what are the key objectives in implementing these algorithms?
- RQ4: What methods can be used to measure traffic behaviour in a real-world scenario and obtain that condition within a simulation?

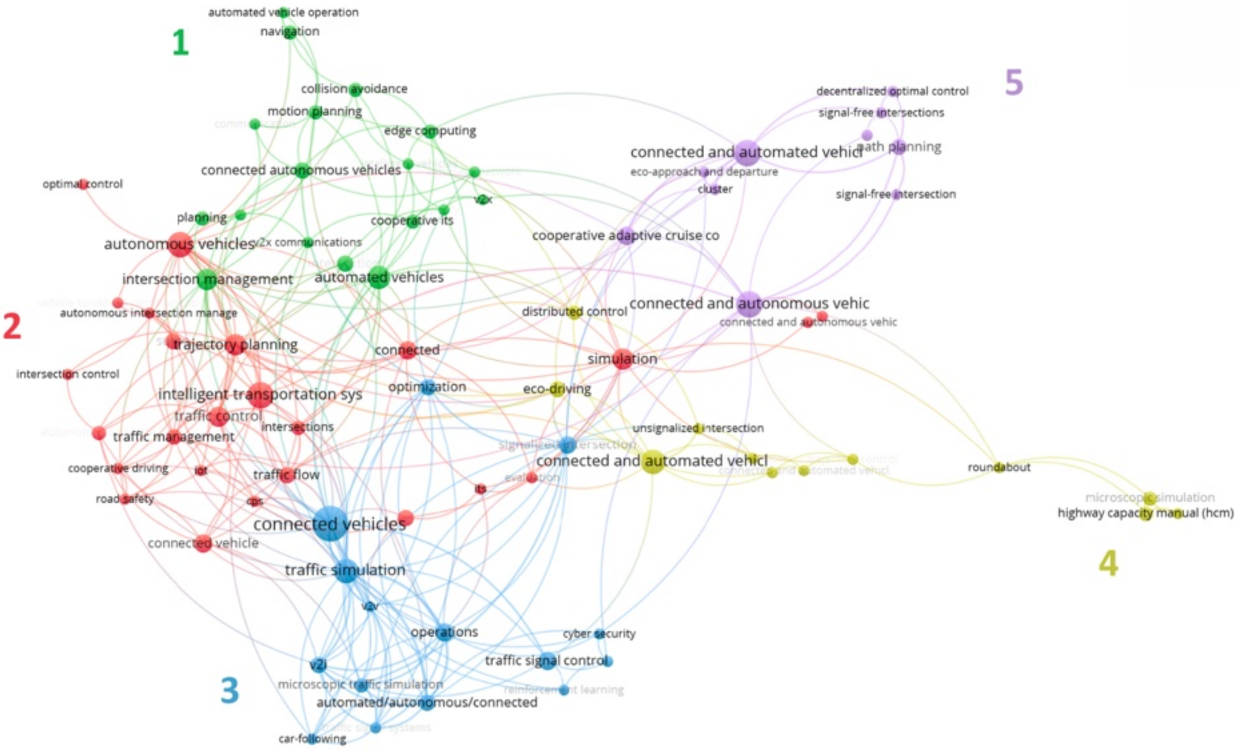

Fig. 2. Co-occurence analysis on keywords defined by Authors.

### C. Search Strategy and Search String

The Scopus database will be used to properly filter the papers selected by the search activity. Papers that are too old will not be considered, as we can still assume a small number of such examples since the research topic is innovative. Specifically, only final research works between the years 2013 – 2023 are included. Only English-language publications are considered. Furthermore, the subject area is limited to engineering, computer science and mathematics considering the field of study of this paper. A single search was implemented to answer all the previously defined questions. This is intended to ensure a link between the articles found and as common a search purpose as possible. The specific search string used is the following one:

**TITLE-ABS-KEY ( ( ( cooperative AND connected ) OR connected ) AND aut* AND vehicle* AND simulation AND ( path OR communication OR ( car AND following AND model* ) ) AND ( roundabout OR intersection ) ) AND PUBYEAR > 2013 AND PUBYEAR < 2023 AND ( LIMIT-TO ( PUBSTAGE, “final” ) ) AND ( LIMIT-TO ( SUBJAREA, “ENGI” ) OR LIMIT-TO ( SUBJAREA, “COMP” ) OR LIMIT-TO ( SUBJAREA, “MATH” ) ) AND ( LIMIT-TO ( LANGUAGE, “English” ) )**

This search resulted in a total of 169 documents.

### D. Analysis of Results

The first analysis carried out shows the number of publications per year in the chosen temporal window. It is important to highlight that before 2013 just 2 papers have been found: this verifies the novelty of the field of study and the hypothesis initially made. Fig. 3 Shows the results of this analysis. It is possible to note an increase in the number of research papers published in this field over the years, which denotes the ever-growing interest in this area validating, moreover, the proposed study and the need for a thorough analysis of the literature on the subject.

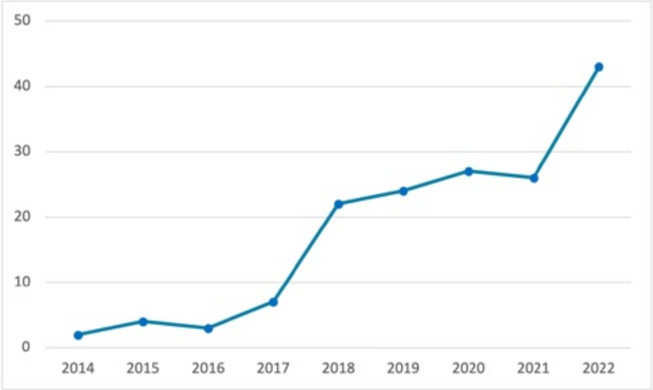

Fig. 3. Number of papers as a function of the year of publication.

Fig.4 presents the number of research outputs per country, spotlighting those most attentive to the topic. Only countries with a minimum number of papers equal to 3 have been considered among the 31 that were found.

Furthermore, an analysis is carried out considering the Authors’ keywords occurrence in all of the papers involved. This is done to understand the specific most treated topics and how they are linked together. Fig. 2 is obtained using *VOSviewer* and considering a map based on the bibliographic data retrieved from Scopus. Co-occurrence analysis is chosen based on keywords as the unit of measure. The correlation of elements is determined by the number of documents in

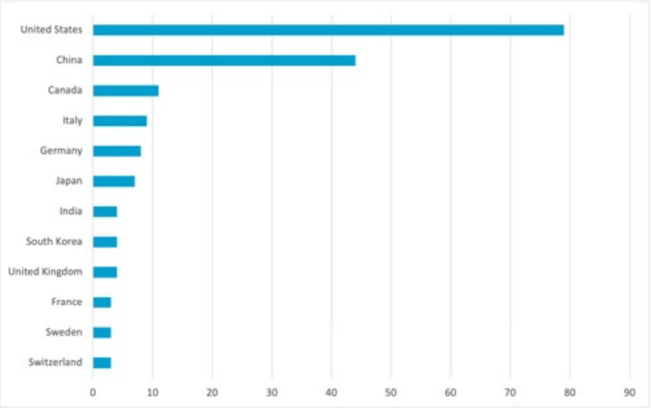

Fig. 4. Number of papers as a function of the country of origin.

which they are found together. The minimum number of co-occurrences is set to 2, to hide keywords used only once and therefore unrelated to any other. A total of 80 keywords is obtained. Finally, to refine the analysis, a minimum cluster size equal to 10 is considered.

The following clusters have been found:

- CLUSTER 1: this first cluster groups keywords referring to navigation, motion planning and collision avoidance. These topics are strictly related since safety inside intersections depends mostly on the algorithm which governs the path management of CAVs. There is also a low occurrence of keywords referring to the type of communication layout implemented, which is critical for path management algorithms.
- CLUSTER 2: this group of keywords is mostly related to traffic management and control and path management. The microscopic traffic simulation and its proper calibration and subsequent representation are predominantly dealt with. One occurrence of cooperative driving control should be highlighted.
- CLUSTER 3: this cluster has as the main topics the connection layout and risk factors. Both comprehensive protocols such as V2V or V2I are mentioned, but also specific applications of reinforcement learning are cited.
- CLUSTER 4: it is the only one specifically referring to the roundabout as the intersection layout. Connected and automated vehicles are described in this specific traffic condition and positive aspects due to the presence of CAVs, such as reduced consumption or crossing time, are taken into account.
- CLUSTER 5: this final cluster deals with CCAVs administration in signal-free intersections and path management for CCAVs considered as a single traffic system. Along with cluster 2, this cluster is the second one which comprehends cooperative logic for automated vehicles and, therefore, it is more pertinent to the purposes of this study.

It is relevant to highlight that all of the clusters described are linked to one another, showing the complexity of the research and its extension to many technical areas. Engineering and data science topics are prevalent. This is also a result of the research methodology adopted. Finally, almost no results refer to the integration of MTS and DDS, showing the difficulty of this process and the still early stage of research in this area.

TABLE I

PUBLISHERS AND NUMBER OF CITATIONS

| **Publisher** | **Journal articles** | **Citations** |
|---|---|---|
| Institute of Electrical and Electronics Engineers Inc. | 73 | 1032 |
| Elsevier Ltd | 16 | 1382 |
| SAE International | 9 | 26 |
| SAGE Publications Ltd | 8 | 83 |
| Springer Science and Business Media Deutschland GmbH | 7 | 15 |
| Elsevier B.V. | 6 | 53 |
| MDPI AG | 6 | 41 |
| Hindawi Limited | 5 | 45 |
| John Wiley and Sons Inc | 3 | 4 |
| Association for Computing Machinery | 3 | 19 |
| American Society of Civil Engineers (ASCE) | 2 | 5 |
| Taylor and Francis Inc. | 3 | 172 |
| Springer Verlag | 3 | 30 |
| MDPI | 3 | 3 |
| Taylor and Francis Ltd. | 2 | 30 |
| IEEE Computer Society | 2 | 2 |
| SciTePress | 2 | 4 |

A final analysis has been carried out on publishers and their citations. Table I presents the results of the journals considered. Only publishers with 2 or more journals are taken into account.

Publishers listed in table I are among the most important ones in automotive engineering and, more broadly, engineering fields. Prominent related sources include: IEEE Transactions On Intelligent Transportation Systems, Transportation Research Part C Emerging Technologies, Transportation Research Record, IEEE Access, SAE Technical Papers, IEEE Intelligent Vehicles Symposium Proceedings, IEEE Transactions On Intelligent Vehicles, IEEE Conference On Intelligent Transportation Systems Proceedings ITSC, Journal Of Advanced Transportation, Journal Of Intelligent Transportation Systems Technology Planning And Operations, Accident Analysis And Prevention, IEEE Transactions On Vehicular Technology, Journal Of Transportation Engineering Part A Systems.

## III. ROUNDABOUT CONFIGURATION INFLUENCED BY CAVs

Roundabouts are mainly described by the number of lanes and legs [20], [35]. The number of lanes refers to how many lanes enter or exit the circulatory roadway. The number of legs defines the number of roads connected to the roundabout. The larger these two variables are, the more complex the scenario becomes. Vehicles may also consider changing lanes within the roundabout and they must pay attention to many more control points both when travelling within the roundabout and at all entrances and exits. Many design variables can be considered when optimising roundabouts geometry [36], as can be seen in Fig. 5. Some of these include the inscribed circle diameter (which is the basic parameter used to define the roundabout's size) and the speed control (which refers to the need to achieve

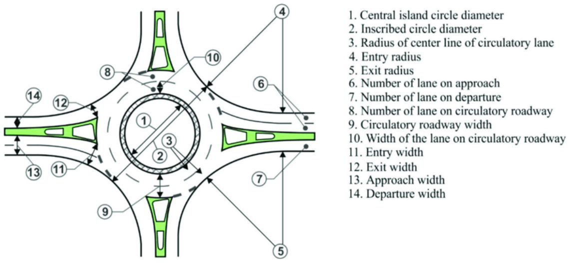

Fig. 5. Roundabout design features adapted from [38].

a certain vehicular speed through the roundabout). The exit and entry path radius are also important factors for safety since they determine both the speed of vehicles through the intersection and whether drivers will yield the right-of-way to circulating vehicles. Authors in [37] illustrated an example of a roundabout's geometry optimisation considering its internal radius and other design elements. As stated in [20] and [35], roundabouts can be classified into three main categories:

1) Mini-roundabouts. Small roundabouts with a fully traversable central island. The inscribed circle diameter (ICD) ranges between 13 m and 28 m. They are characterised by low speeds and traffic volumes and they are populated mostly by light vehicles.
2) Single-lane roundabouts. This type of roundabout is characterised by having all single-lane legs. The ICD is between 27 m and 55 m. A splitter island should be provided at all the legs.
3) Multi-lane roundabouts. They have at least one entry with two or more lanes. The ICD ranges between 30 m and 100 m. The number of lanes inside the circulatory roadway can vary accordingly to the number of legs and their lanes.

Considering the roundabout categories in the order just described, it is possible to highlight increasing entry and exit lane widths, traffic volumes and dividing island dimensions. Furthermore, single-lane and multi-lane roundabouts show similar speeds at entries, gyratory circle and exits, and non-traversable central islands.

The roundabout design process depends on all its geometric properties and the final performance achieved [39]. For example, as stated in [40], the speed at which vehicles travel into a roundabout is strictly connected to the diameter of the central island, the width of the circulatory roadway, the width of the entry lane and the inclination angle of the entry lane. Usually, the design process is iterative: starting from the standards and guidelines available, it is possible to obtain geometry, visibility, cross-sectional features and spatial limitations, which are finally compared with performance requirements.

One of the key performance indicators of a roundabout is its *capacity*, intended as the sum of arrival flow rates when the entry lanes reach full saturation and at least one vehicle is always queued at the give-way line of the entry lane [41], [42]. It is a crucial key performance indicator since the queue lengths and queuing delays depend on it. There are three main categories of models to evaluate this parameter:

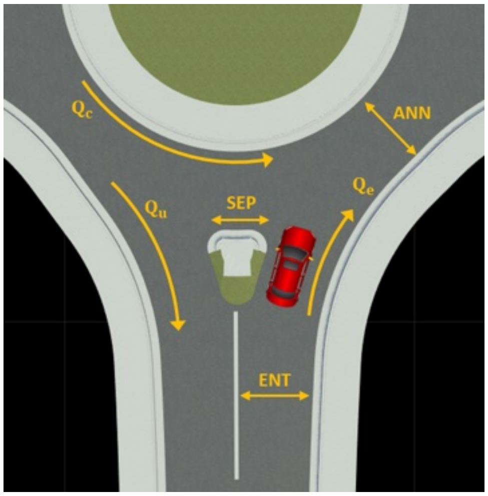

Fig. 6. Parameters to calculate capacity according to SETRA model [43].

- *Statistical (empirical) models* are based on the regression of field data.
- *Analytical (semi-probabilistical) models* are based on the gap acceptance theory.
- *Microscopic simulation models* are based on the modelling of vehicles' kinematics and interactions.

In [39] Authors present a detailed description of these models and their negative aspects. Statistical models describe the relationship between input parameters and capacity but do not investigate the theoretical evidence of those relationships. This must be carefully taken into account, especially in atypical scenarios for which the validity of such models is required to be proven. A further criticality of these models resides in the constraints due to the data used for model development, which may cause almost no key performance parameter to be significant. Analytical models do not directly quantify the interrelation between the geometry and the capacity of a roundabout. They depend on the formulation of an intermediary vehicle-to-vehicle interaction model. Since driver behaviour is highly variable, this may lead to weak relationships with key performance indicators.

Microscopic simulation models suffer from the priority-sharing phenomenon, which occurs at high circulating flows. The result is an under-prediction of entry capacities, due to the simple gap acceptance algorithms used for these models. Furthermore, they can also have problems in representing multi-lane roundabouts, since no difference in vehicle behaviour is described for the nearside and the outer lanes approaching the roundabout.

SETRA capacity model belongs to the first group and relates the capacity of the roundabout to geometric features and to traffic flow measurements:

$$K = f(Q_c, Q_u, SEP, ANN, ENT) \tag{1}$$

indicated in Fig. 6.

An example of a model belonging to the second set is presented in the Highway Capacity Manual (HCM) [44]: the critical gap is defined as the minimum time between successive major stream vehicles, in which minor street vehicle can make a manoeuvre [45]. In the case of a roundabout, the major stream is represented by the vehicles already in the circulating roadway, while the minor streams are the entry lanes. This kind of model allows to take into account the typical driver behaviour associated to a specific country.

In [46] Authors describe an application example of a microscopic simulation model. A Swiss roundabout capacity model based on CETUR empirical model has been obtained, finding the following equation describing the entry flow rate:

$$Q_e = 1500 - \frac{8}{9}(\beta Q_c + \alpha Q_x) \tag{2}$$

where $\beta$ depends on the number of circulating lanes, $\alpha$ describes the impact of vehicles leaving the roundabout and $Q_x$ represents the immediately upstream.

Thanks to the microscopic simulation model, the Authors were able to obtain a clear understanding of the parameter $\alpha$ and how it is related to all other parameters.

These differences in the capacity calculation come from the fact that optimizing the design of a roundabout is not a simple task: in fact, conflicting objectives have to be examined [47]. The roundabout should ensure the possibility to cross the intersection without stopping completely, as a feature distinguishing it from traffic lights and give way/stops, so the speed and the traffic flow should be as high as possible. On the other hand, safety must be granted and collisions must be avoided, so it is necessary to find a compromise.

To identify the goodness of a roundabout, it is possible to define many key performance indicators. Some of them are listed below:

- **Capacity [veh/h]:** its calculation depends on the selected model [48], as well as the parameters involved in the computation. It should be as high as possible in order to guarantee the efficiency of the infrastructure.
- **Reserve capacity [veh/h]:** also called spare capacity, it is the difference between the capacity $C$ and the entry flow $Q_e$ [49]

  $$R_c = C - Q_e \tag{3}$$

  It should be in the range of 25-80%. If it is higher than 80% for the greatest amount of time, the roundabout may be over-dimensioned. On the contrary, if it is lower than 25%, the infrastructure is prone to get congested.
- **Average stop delay [s/veh]:** it is the time that a vehicle waits in the entry lane while queueing, before having a sufficient time gap between two vehicles, necessary to enter the circulating flow safely [50], [51]

  $$d = \frac{3600}{C} + 900 * T\left[(x-1) + \sqrt{(x-1)^2 + \frac{3600 * x}{450 * C * T}}\right] \tag{4}$$

  Here $C$ is the capacity [veh/h], $x$ is the saturation degree of the entry lane [-] and $T$ is the period of analysis [h]. This parameter is strictly connected to the capacity of the roundabout.
- **Mean geometric delay [s/veh]:** it is the mean time lost by a single vehicle, without experiencing any slowdowns due to conflicts between traffic flows, to cross the intersection at standard velocity [52]

  $$d_g = \frac{P_s}{100} * d_s + \left(1 - \frac{P_s}{100}\right) * d_u \tag{5}$$

  Here $P_s$ is the percentage of vehicles which have to stop at approach legs due to queue, $d_s$ is the geometric delay for the vehicles that have to stop at approach legs due to queue [s/veh] and $d_u$ is the geometric delay for vehicles which do not have to stop at approach legs due to queue [s/veh]. The first quantity depends on the degree of saturation of the infrastructure, while the latter two values are related to the kind of manoeuvre carried on by the vehicles (right turn, manoeuvre to go left, go-through straight crossing, u-turn).
- **Queue length [-]:** it is the number of vehicles that are queuing. The length of the queue generated in the entry lane [36] is:

  $$L_{queue} = \frac{d * Q_e}{3600} \tag{6}$$

  Here $d$ is the average stop delay [s/veh] and $Q_e$ is the entry flow [veh/h]. $L_{queue}$ can be multiplied by the average length of the vehicles $L_m$, thus obtaining a measure expressed in meters. Queue length is strictly connected to the average stop delay and as a consequence to the capacity of the roundabout.
- **Fuel consumption [g/s]:** it can be estimated by means of the formula proposed in [53]

  $$F(t) = \begin{cases} \alpha_0 + \alpha_1 P(t) + \alpha_2 P(t)^2 & \forall P(t) \geq 0 \\ \alpha_0 & \forall P(t) < 0 \end{cases} \tag{7}$$

  Here $P(t)$ is the instantaneous vehicle power [kW], while $\alpha_0$, $\alpha_1$ and $\alpha_2$ are model parameters. In some traffic simulators, such as SUMO (Simulation of Urban MObility [54]), it is also possible to estimate fuel consumption directly in the simulation, setting the parameters on the emission class of the vehicle. SUMO can be used also to compute the emissions of pollutant agents (estimation based on [55]).
- **Motion comfort [-]:** it is the description of the overall driving comfort perception of vehicle occupants during the roundabout crossing. It can be described as a function of acceleration, jerk, and direction. An accurate description of this indicator can be obtained through the use of dynamic driving simulators from empirical data. Authors in [56] proposed a study to obtain a clear parametrisation of expected discomfort given acceleration pulses. The thresholds found on accelerations and jerks, based on their direction, are crucial to develop motion planning algorithms.

In this context, the introduction of CAVs leads to additional considerations. In [57], the impact of the introduction of CAVs on roundabout design is studied. If vehicles exploit a V2V communication system, they can accept a smaller gap when entering the central circulatory roadway, because they know with higher precision the position and the velocity of the incoming cars. This allows to increase the capacity of the roundabout and, as a consequence, to decrease the length of the queues that may form at the entries. Considering this aspect, it is possible that the geometrical elements of the roundabouts should be rethought, taking into account also the chance to have a mixed traffic scenario, in which both CAVs and human-driven vehicles are present. In this case, as highlighted in [58], the intersection can be equipped with roadside sensors or video detection points in order to track the movements of non-automated vehicles. Including this information in the input data of the control algorithm allows the system to detect potential conflicts and correct the actions of automated cars.

One of the configuration aspects that most affects the traffic operation in roundabouts is the number of lanes. In [59], the impact of the introduction of CAVs on traffic operations at roundabouts is studied, focusing in particular on capacity calculation. The Authors started from the model present in HCM and developed some Capacity Adjustment Factors (CAFs) in order to account for the presence of automated vehicles at the intersection. They studied the situation by applying a Cooperative Adaptive Cruise Control (CACC) to the cars so that they could take advantage of the connectivity. The results show how the introduction of CAVs can improve the capacity of roundabouts, but this effect is more pronounced on single-lane roundabouts with respect to double-lane ones. This difference increases even more if the traffic demand raises. This could be related to the fact that, if in a single-lane roundabout the first vehicle is an automated one, all the others end up following it in a platoon and the introduction of CAVs is clearly practical on traffic operations. If the roundabout considered has two or more lanes, such as the ones observed in [60], a human-driven vehicle is more likely to change lane in an attempt to overcome the automated car, which may move slower with respect to the human-driven one, and so a CAV can be seen as an obstacle creating a delay.

Finally, when considering CAVs, it becomes essential to account for passenger driving comfort. This indicator assumes significant importance in the perspective of real, widespread and accepted use of AVs. Geometric quantities, such as the inscribed circle diameter of the roundabout, must therefore be obtained taking into consideration their effect on the movement of CAVs or CCAVs and the accelerations and jerks produced [56].

## IV. GAP ACCEPTANCE MODELS

Considering the design process of the roundabout, as described in section III, *capacity* is one of the main KPIs used to obtain the final roundabout geometry. A relevant method to estimate capacity considers the involvement of *critical headway* and *follow-up headway*, performed by analytical gap-acceptance models [61]. As described in detail by the Authors in [62], critical and follow-up headway are defined as the psycho-technical parameters of drivers. The headway is defined as the minimum amount of time between vehicles, taken from a population of headways in the mainstream at the roundabout. If the headway is equal to or greater than a critical value, the driver can safely enter the roundabout from a subordinate entry. This critical value is typically an average given in statistical terms. The follow-up headway is expressed as the time between the departure of the first vehicle from the roundabout entry and the departure of the next vehicle using the same major street headway under the condition of queuing at the roundabout entry. Several models to estimate the values of these two parameters have been developed over time. Special attention should be devoted to how to manage randomness and variability [63]. Below, some of the most important models are presented and analysed considering application examples. Please consider that gap and headway are synonyms.

One of the most popular gap-acceptance models to estimate the critical gap is Raff's model [64]. Originally, Raff's model considered lags, defined as the amount of time between a vehicle arriving at a stop or yield line in the minor stream and the arrival of the next vehicle in the major or priority stream. Instead, in its updated version, the critical gap is obtained by considering rejected and accepted gaps. They are tabulated in group intervals and used to obtain their probability of appearance for each group. These probabilities are plotted and the critical gap is represented by the intersection point of the two lines related to accepted and rejected gaps, respectively. Authors in [65], present a definition of critical headway, employing Raff's model and using both geometrical and operational data of the roundabout. Firstly, a collinearity analysis is carried out to understand which are the independent parameters. Secondly, a correlation model is used to build a linear regression and predict the critical gap value. The model shows that the parameters most affecting the critical gap estimation are the circulating volume of vehicles, the distance between neighbouring legs and the approach entry width. Authors in [66], describe further Raff's revised model based on the calculation of the maximum rejected gap distribution, namely Maximum Likelihood Model. Differently from the baseline approach, distributions are not considered to be uniformly distributed. Authors demonstrated that the updated version is able to calculate better estimates and provide the standard deviation of the critical gap to obtain a more comprehensive description.

Another gap-acceptance model is Wu's Model [67]. It is based on the macroscopic equilibrium of the rejected and accepted headways. Wu's model introduced some positive aspects, such as a solid theoretical background, robust results, independence from any model assumptions and a simple calculation procedure. Authors in [68] describe an application of Wu's model to obtain the critical gap of a two-lane roundabout. On the intersection, cameras have been mounted to study the traffic behaviour in terms of arrival and departure time of vehicles. The critical gap is obtained by solving the following equation.

$$F_{tc}(t) = \frac{F_a(t)}{F_a(t) - [1 - F_r(t)]} = 1 - \frac{1 - F_r(t)}{F_a(t) - [1 - F_r(t)]} \tag{8}$$

$F_a(t)$ is the probability of the accepted gaps, $1-F_r(t)$ is the probability of the rejected ones and $F_{tc}(t)$ is the probability distribution function of the critical gap.

The last presented gap-acceptance model is the Simple Logit Model. It considers the cumulative probability of both rejected and accepted gaps, obtained using Simple Logit. Following this method, the critical gap is defined at the intersection between the cumulative probability distributions of accepted and rejected gaps, respectively. The method is solved by considering the following mathematical equation.

$$P = \frac{1}{1+\exp-(\beta_0+\beta_1 * x)} \tag{9}$$

$P$ is the probability of gap acceptance, $\beta_0$ and $\beta_1$ are regression coefficients and $x$ is the length of the gap. Authors in [69] described the application of this model for five single-lane four-leg mini-roundabouts. The required geometric and traffic parameters of the roundabouts have been obtained using the so-called photographic method, which employs videos. This model, compared to the others described, is generally used to propose a sensitivity analysis of all the considered independent variables.

## V. SIMULATION SOFTWARE

The most widely used software for microscopic traffic simulation environment are introduced. They are:

1) PTV VISSIM
2) SUMO (Simulation of Urban MObility)

VISSIM is a commercial tool to implement microscopic, discrete highway and urban traffic simulations. As described by Authors in [70], it can be used, for example, to investigate heavily utilised motorways, identify system performance and bottlenecks, implement corridor studies on arterial with various types of intersections and analyse actuated and adaptive signal control strategies in urban networks. The following models are used to obtain the final simulation:

- A mathematical model used to represent the transportation supply system.
- A demand model which generates the people and vehicles trips in the network.

Car-following models, lane-changing logic and paths and routes are examples of features which can be introduced in VISSIM. Both private and public transport systems can be inserted in the simulation environment by defining vehicle categories, geometrical characteristics and specific properties such as timetables, arrival and departure times. Traffic control strategies can also be built by defining the specific type of intersection and its resulting right-of-way logic and peculiar priority rules. As the environment has been completely defined, the simulation can be carried out in 2D or 3D and numerous measures of effectiveness can be acquired, such as delay, speed, vehicles' density and queues' properties. Output data can be easily processed, for example, in Excel.

SUMO is an open-source, highly portable, microscopic and continuous traffic simulator [71]. It can be used to create complex simulation environments with many types of vehicles, different lanes and different kinds of intersections (regulated, non-regulated, with traffic lights). To be able to run a generic simulation three files are needed:

- The simulation network, containing all edges, lanes and trajectories that any vehicle can follow.
- The route file, in which all vehicles' routes are described.
- The configuration file which commands the simulation and links all the other files together.

All of these files can be obtained by using *Netedit*, the graphical network editor, or by computing them following the guidelines and requirements given by SUMO tutorials and examples. Also for this second software, it is possible to implement both private and public transport systems, car-following models and specific routes. SUMO represents every vehicle as a single point, for which it is possible to have many different details at every time step such as position, speed or fuel consumption. Vehicles move along trajectories, which the user can customise, defined as a list of points linked together using straight lines. Data can be retrieved directly from SUMO or by using TraCI (Traffic Control Interface), a SUMO library giving access to a running road traffic simulation. It allows retrieval of any data about the simulation status and all the vehicles' properties. It uses a TCP (Transmission Control Protocol) based client-server architecture.

## VI. COMMUNICATION APPROACHES AND PATH MANAGEMENT ALGORITHMS OF CAVS

From a network architecture point of view, there are two main approaches to manage traffic operations with CAVs at bottlenecks such as the roundabout [21].

The first one is the use of a *centralized system*: a central controller gathers all the information from the approaching vehicles in the communication range, makes choices and gives information back to the vehicles. This kind of network architecture is referred to as vehicle-to-infrastructure communication (V2I).

The second approach is based on a *decentralized* or *multi-agent system*: in this case, the decision-making agents are directly the vehicles involved in the intersection area. This approach exploits the so-called vehicle-to-vehicle communication (V2V). In [86], it is highlighted that the computational effort of a centralized controller in a V2I system increases with the number of the vehicles involved, so guaranteeing some individual decision-making ability to the cars, shifting to a V2V approach, or combining the two, may be an important aspect to consider. In [75], it is stated that the cost of installing the infrastructure able to perform a V2I communication on every intersection would be considerably high, so relying on V2I can be impractical to some extent. Furthermore, if the central controller fails, automated vehicles may not find alternative means to manage their coordination. In this sense, V2V may represent a better option. On the other hand, V2V is more complex to manage, due to the fact that the vehicles involved are in the neighbourhood of the intersection only for a limited time, so the control logic must work precisely only when it is needed [87].

In [21], two main kinds of algorithms useful to manage traffic operations with CAVs at intersections, depending on the

TABLE II

PATH MANAGEMENT OF CAVS: STRATEGY, SIMULATION ENVIRONMENT AND OBJECTIVE

| Reference | Path management strategy | Simulation Environment | Objective of the strategy |
|---|---|---|---|
| [58] | Intersection management using cooperative adaptive cruise control | Four-way roundabout, stop signs and traffic signal intersections (numeric simulation), using MATLAB | Minimising intersection delay with no crushes |
| [72] | Vehicles are divided into clusters and a combinatorial optimization problem is solved to obtain vehicles sequence. | Four-leg, single-lane roundabout (numeric simulation), using MATLAB | Smooth traffic flows near the capacity |
| [73] | Optimisation problem that includes vehicle dynamics and collision-avoidance | Four-leg, single-lane roundabout (numeric simulation), using VISSIM | Minimizing the distance of CAVs to their destinations and their acceleration magnitudes |
| [74] | Hierarchical coordination framework based on upper-level scheduling and lower-level optimal control | Two adjacent intersections. Validated also for multi-lane roundabouts (numeric simulation), using VISSIM | Minimising travel time and optimising transient engine operation and, accordingly, energy consumption. |
| [75] | Collision Detection Algorithm for Roundabouts | Four-leg, single-lane and double-lane roundabouts (numeric simulation), using AutoSim | V2V intersection protocol for improved safety |
| [76] | Optimisation problem divided into two substages | Single-lane roundabout (numeric simulation), using VISSIM | Arrival time, accelerations and decelerations fluctuations |
| [77] | Control algorithm based on 5G communication with an intersection management unit | Intersection without a stop such as roundabouts (numeric simulation), using DASHX-SIM | Minimisation of traffic delay, reduction of emissions and promotion of road safety |
| [78] | Optimisation problem subjected to dynamic and static constraints | A four-leg roundabout, a traffic-signal controlled intersection and a stop sign intersection (numeric simulation), using VISSIM | Lowest possible delay satisfying constraints |
| [79] | Real-time optimal controller | Multi-lane roundabout (laboratory simulation) | Experimental validation of the optimisation problem minimising travel time and avoiding collisions |
| [80] | Optimisation algorithm based on a model predictive control solution technique | Four-leg single-lane roundabout (numeric simulation), using VISSIM | Minimising travel time within the intersection |
| [81] | Deep Reinforcement Learning algorithm | Three-leg, single-lane roundabout (numeric simulation), using SUMO | Travel time optimisation |
| [82] | Optimisation problem solved analytically | Single-lane roundabout (numeric simulation), using VISSIM | Minimisation of accelerations and decelerations with no rear-end collisions and vehicle speed limit |
| [83] | Game theory deep learning-based problem | Single-lane roundabout (laboratory simulation) | V2V cooperation between automated wireless-connected vehicles |
| [84] | Coordination and cooperation using V2V and V2I communications based on a semaphore flag logic | Single-lane roundabout (laboratory simulation) | Validation of cooperative intelligent transportation system |
| [85] | Deep Reinforcement Learning algorithm | Three-leg and four-leg, single-lane roundabout (numeric simulation), using SUMO | Emission, Travel time and driving comfort optimisation |

objective function taken into account are distinguished. We can have *reservation-based algorithms*, exploiting V2I or V2V communication, in which each vehicle requests a reservation to use the conflict area inside the intersection. If the request is not accepted, the vehicle requests a reservation again in the following time step, and so on until it has permission to occupy the conflict zone. Another approach is the use of *trajectory-based algorithms*, in which V2V and V2I may be combined. In this case, the objective is to identify the optimal trajectory for all the vehicles involved in the system, possibly promoting the formation of vehicle platoons.

Recently, as an alternative to V2I or V2V, a vehicle-to-network-to-vehicle V2N2V approach has been proposed. In particular, it has been developed use case 1 of the European project AI@EDGE [88]. One of the aims of the project is to study the movement of automated vehicles into a roundabout and implement a technology able to guide them through this kind of infrastructure, exploiting artificial intelligence and 5G networks.

The literature presents various examples of V2I and V2V or even a combination of them. Table II contains the main features of the literature cited in this section.

Authors in [72] developed a system in which the central controller is installed in the cloud, so it is not in a physical roadside unit. It is able to receive data from the vehicles regarding their current position, velocity and acceleration, that the central controller uses to compute the optimal sequence of the vehicles at the merging points. After that, the target merging times are provided to the vehicles, which decide autonomously their level of acceleration. This communication scheme allows to improve the capacity of the roundabout and to reduce idling time and fuel consumption while ensuring a smooth acceleration profile, so as not to compromise the comfort of the passengers. In this work, the issues related to communication delays are not specifically addressed, since the system is assumed to be able to transmit coordination information without significant delay. This aspect should be further investigated with a view to implement this traffic control system in a real environment.

In [73], Authors presented a methodology to control the CAVs path inside the roundabout, formulating an optimisation problem which considers as design variables the vehicle's accelerations and as state variables the speed and position of CAVs over time. The solution to the problem posed is divided into three sections. 1: convexification, during which constraints are convexified and represented with a linear constraint using their first-order Taylor expansion equation. 2: decomposition, thanks to which the optimization problem is decomposed into sub-problems by adding auxiliary constraints. 3: transformation, which guarantees non-convex sub-problems obtained in step 2 to converge correctly.

In [74], Authors provide a hierarchical coordination framework for CAVs consisting of two levels: an upper-level scheduling problem and a lower-level optimal control problem. Two adjacent intersections are considered as the simulation environment. A *coordinator* is positioned inside the network and stores geometric parameters, CAVs' paths and planned trajectories. Once connected and automated vehicles enter the control zone, they receive an ordering index based on their entry time and a tuple is created, containing all the zones that the vehicle will pass through. If two or more vehicles share one or more intersection zones, conflict zones are defined in which vehicles' order is obtained based on their ordering index. Differently from [72], this algorithm accounts also for the safety of vehicle occupants in terms of crash avoidance strategies. The objective of each CAV is to minimise travel time and improve traffic throughput. In the upper-level problem, a decision-making scheduling process is addressed to minimise travel time inside the control zone. In the lower-level problem, each CAV solves an optimisation problem to obtain the control input in terms of acceleration which satisfies the schedule defined before and minimises the energy spent during the motion. The path management algorithm proposed reduced travel time and has also been validated for multi-lane roundabouts.

In [75], Authors implemented an intersection management protocol for V2V-equipped automated vehicles. The Authors considered the roundabout as a grid divided into small cells and they assumed that vehicles have access to a digital map providing road and lane information. Each of the involved vehicles creates a trajectory cell list, so a list of all the cells the vehicle will occupy during its path. This list is broadcast to the surrounding vehicles, and the onboard collision detection algorithm compares the path of the sender with the ones received from the other cars involved in the intersection. In case there is any common cell, a potential collision is detected: the algorithm returns the ID of the first conflicting cell and assigns the priority based on the time the vehicles arrive at the roundabout and the importance of the road they come from. This algorithm is similar to the one proposed by Authors in [74], proving the possibility of employing equivalent strategies, although different communication protocols have been employed. This system allows to reduce delays and avoid collisions inside the roundabout, as it prevents vehicles from entering the conflict cells at the same time. The protocol is designed for automated vehicles that exploit V2V communication for cooperative driving, but it can be adapted also to give alerts to human drivers in case of mixed traffic. In this work, the cell subdivision of the roundabout is coarse, so a deterministic algorithm for the definition of the sequence of vehicles is sufficient. In order to better represent a real situation, a finer mesh could be generated to discretise the road. In this case, the possible sequence of cells to execute a manoeuvre may become variable. Optimization algorithms could represent a valuable option to identify the best sequence of vehicles to navigate the roundabout.

In [76], Authors propose a method to optimally control CAVs at roundabouts under a fully CAV environment. CAVs are equipped with V2V and V2I communication that can receive planned trajectories from a central controller. To obtain the final path, a two-stage optimisation model is formulated. In both cases, an optimisation problem is proposed, firstly optimising the arrival time of each vehicle and, thereafter, minimising the accelerations and decelerations fluctuations, similarly to [72]. Finally, also a collision avoidance model is considered by defining a safe headway distance as a constraint to the optimisation problem.

In [77], Authors describe a highly efficient traffic planning system, called DASHX and based on open-source DASH-Sim, which makes use of 5G to ensure stable and fast communication between automated and connected vehicles in intersections without a stop. This path management algorithm ensures both a reduction in travel time and driving comfort, monitoring the vehicle's accelerations. All connected and automated vehicles communicate with an intersection management unit to report their status and requirements in terms of their path. Firstly, the specific intersection configuration is analysed, considering some core features like its lanes, routes and conflict points and dividing it into harmonisation, dash and crossing zones. If compared with the definition of different levels for the control algorithm proposed by Authors in [73] and [74], this is the first example of geometric partitioning of the roundabout. In both cases, a simplification of the control algorithm into sub-problems is proposed, but operating on different levels. Secondly, it is developed the vehicle status model which captures the dynamic information streamed from incoming vehicles. This dynamic status is made up of many vehicle data, such as the distance to the intersection, the initial speed and the acceleration. Finally, the algorithm considers also specific constraints depending on passengers' comfort preferences in terms of maximum accelerations, minimum gap to front vehicles or safety restrictions. The control algorithm is divided into three stages: as CAVs approach the harmonisation zone, they receive all their requests, then, the vehicles' motion is planned and a crossing sequence is determined. Finally, possible conflicts are resolved and the final planes are sent to vehicles, updating a scheduling vector. DASHX has been tested in many intersections without stops, like roundabouts, four-way, five-way or six-way intersections proving to be better than the state of the art in optimising transportation efficiency, promoting road safety and reducing emissions.

In [78], Authors proposed a combination of 2 approaches (V2I and V2V). A scheduler is positioned at the intersection to assign time slots to the vehicles willing to cross the conflict zones. Cars share their past, current and expected future positions, their velocity and their acceleration with the other vehicles and with the central scheduler. This combination allows to apply an optimal control strategy to determine the time instants in which vehicles are allowed to enter the roundabout (V2I), but also to exploit V2V communication in order to include car-following and collision avoidance models. As considered in [72], also in this paper "perfect communication between the vehicles themselves and between the scheduler and vehicles is assumed". In a real environment, communication delays exist, so there is a time lapse between the moment in which the message is sent and the instant in which it is received. This issue should be tackled in future studies to understand the influence of this aspect on the performance of the control system.

In [79], Authors describe a multi-lane roundabout optimal control. The roundabout is divided into a control zone, which ends at each roundabout exit and a coordinator is associated with it. This piece of infrastructure is just a database and it stores information about the roundabout's geometry and the CAVs trajectory information. Every time a CAVs enters the control zone it solves an optimal control problem, minimising a function of its acceleration considering a number of constraints. Once the first problem is solved, for every CAVs is obtained the minimum travel time not violating any imposed constraints. Also in this case study, no delay is considered neither for the V2V nor for the V2I communication configurations, limiting the effectiveness of the results obtained. The Authors successfully validated experimentally the optimal control proposed and proved the ability of this algorithm to correctly move CAVs without stop-and-go driving avoiding collisions.

An example of a trajectory-based approach is developed by the Authors in [58]. A model of CACC is implemented to manage traffic operations at an intersection, with the objective to minimize total delay and ensuring that no collision occurs. The intersection is equipped with a controller which receives requests from vehicles approaching the intersection zone, optimizes vehicle movements and sends the optimum strategies to the vehicles, in terms of coordinates and velocity associated with each time instant. It also computes delay and fuel consumption for each vehicle. In this work, the system is assumed to work in real-time. In order to achieve this result, a dedicated short-range communication is assumed to be used for V2I/V2V communication. It has been chosen because these communication systems ensure low latency and are designed to manage multipath transmissions. The area covered by the signal transmission is assumed to be 200m in each direction from the centre of the intersection, which is a typical distance for dedicated short-range communication systems.

In [80], Authors developed a method to control the trajectory of CAVs in roundabouts with a mixed fleet of connected and automated vehicles and human-driven vehicles. To manage the CAVs' paths, a model predictive control solution is proposed, considering also the driving behaviour of human-driven vehicles. At each time step, the speed and position of all vehicles in the network are obtained as state variables and used in a decomposition-based methodology. A four-leg single-lane roundabout in Vissim is considered to test the algorithm proposed. The Authors, differently from other examples, such as [72] and [79] did not consider the vehicle dynamics and the related capacity of vehicles to follow the acceleration profile obtained from the control algorithm. Furthermore, no modification in the driving behaviour of human-driven vehicles is considered in the presence of CAVs. The developed approach results to be heavy from a computational point of view, thus being able to consider machine learning in the future in order to solve this issue and extend the proposed solution.

In [81], Authors used deep reinforcement learning to train two automated vehicles to lead as many fleets of conventional vehicles onto a roundabout. They obtained two policies, one with noise injected into the state and action space, and another without any noise. After that, they transferred the learnt policies to a scaled smart city without fine-tuning. The results show that traffic into a roundabout can flow successfully, but the noise-free policy produces severe slowdowns, while the noise-injected one leads to a reduction in travel time. This is due to the fact that when the policy is transferred to an environment which is similar but not exactly identical to the one used to train the system, the noise-injected policy sees the mismatches of the two scenarios as just another form of noise, so it is able to account for it successfully, unlike the noise-free policy.

In [82], Authors developed a control algorithm for connected and automated vehicles in a single-lane roundabout with mixed traffic. It is applied a geometric classification of the roundabout, as proposed by Authors in [77]. The roundabout is divided into a control zone and a merging zone. When each single CAV enters the control zone, a first-in-first-out logic is used to define the control queue. While driving through the intersection, the control input in terms of accelerations and decelerations and the vehicle's speed are monitored to make sure they are within certain limits. The control algorithm aims at minimising the control input for each vehicle from the time it enters until the time it exits the control zone. The authors formulated an optimisation problem solved analytically. The coordinator inside the control zone is able to receive data from all the vehicles in the network and it is not involved in any decision. Thanks to simulation in VISSIM, the control algorithm proved to be able to positively influence traffic inside the roundabout, reducing the total travel time by 51% and fuel consumption by 35%. An efficient control is obtained for high market penetration rates of CAVs, due to the instability introduced by human-driven vehicles. No consideration was made on driving comfort or communication delay during the traffic simulation. This makes the results obtained limited and not applicable to a real condition.

In [83], Authors proposed a V2V decision making process using game theory. The non-zero-sum game with the introduction of smart vehicles and prisoner's dilemma is proposed. Several players, in this scenario represented by vehicles, must make choices that potentially affect other players, creating a cooperative logic. Each automated vehicle has two states. It can be an entering vehicle and a circulating vehicle. The entering vehicles can send the angle at which it saws other circulating vehicles, its current travelled distance and its current speed. Circulating vehicles send information to other entering vehicles. If compared with the V2V scheme proposed by Authors in [75], vehicles do not share information

Fig. 7. Dynamic driving simulator of Politecnico di Milano.

about other vehicles' future trajectories, but only take into account what their sensors can detect. This implies a limitation on the cooperative strategies that vehicles can achieve since it is based on much more limited information. This scenario has been tested with wireless-connected mobile robots. When considering real traffic scenarios, more factors must be considered.

In [84] Authors presented a framework of wireless cooperation between automated vehicles in a roundabout. The network is composed of two types of nodes. A coordinator receives data from vehicles in the simulation and monitors the cooperation process. A mobile sensor represents automated vehicles and has the ability to react the environment-changing state. Vehicles are robots equipped with an aluminium chassis, batteries and control electronics. The cooperation algorithm receives all vehicles' start and end positions and defines a priority. During the simulation, vehicles obtain their priority and communicate in real-time their position. The experiment proved the ability of intelligent transportation systems to correctly orchestrate the traffic within a roundabout. It is important to highlight that vehicles not only exchange information but also cooperate to achieve the final controlled path.

In [89], Authors proposed an approach to implement a cooperative control of CAVs based on a bi-level coordinated merging. Vehicles in the entry lanes approaching the roundabout are made to form clusters by the high-level controller, while the low-level one calculates the optimal sequence of roundabout merging times, with the aim to minimize the total time taken for all approaching vehicles to enter the roundabout but minimally affecting the movement of the vehicles already present in the circulatory roadway. Their strategy can be implemented in real-time, but once platoons are formed since the gaps between the vehicles are very small, any communication delay can produce a detrimental effect leading to instability of the cluster and to potential collisions.

The European Consortium AI@EDGE [85] has initiated a research focused on the applications of Artificial Intelligence (AI), 5G and EDGE computing, referring to roundabout traffic. In use case 1, the traffic within a virtual roundabout is simulated by exploiting the dynamic driving simulator of the Politecnico di Milano, Fig. 7.

A dedicated artificial intelligence algorithm is derived to drive CCAVs within a four-leg roundabout. CCAVs are connected by a V2N2V (vehicle-to-network-to-vehicle) scheme. They send their kinematic data to a MEC/edge computer, installed ideally in the centre of the roundabout. It also receives data about position, speed and acceleration from all the vehicles involved in the scenario, i.e. by both conventional and automated ones. By means of an artificial intelligence algorithm based on Q-learning, the MEC/edge node defines the speeds of each automated vehicle, with the aim to obtain a safe traffic flow and a reduction of air pollution due to vehicles' movement. The edge node sends via 5G to the automated vehicles the instructions to accelerate or to brake. It is assumed that non-automated vehicles, i.e. the ones simply driven by humans, just send data (position, velocity and acceleration) to the network but they do not receive any data to control their respective speed. In this context, vehicles exchange information among themselves without relying on a broadcast from an infrastructure authority, basing their decisions on a shared policy defined by an artificial intelligence algorithm executed at the edge server.

Mixed traffic is simulated within the virtual roundabout, i.e. there are both CCAVs and virtual cars driven by virtual drivers [90]. Such last cars send to the edge computer their kinematic data but do not receive information on traffic concerning the roundabout (in order to avoid cognitive overload for the virtual driver). An actual human driver on board the cockpit of the driving simulator drives in the mixed traffic.

This case study is also an example of the successful integration of microscopic traffic simulation and virtual reality simulation in a dynamic driving simulator. Thanks to the presence of a human in the loop, it was possible to obtain information about the transportation network performance and the human perception of driving comfort, safety and traffic flow.

Early results show that a panel of human drivers seem happy with the interaction with CCAVs. Additionally, the virtual roundabout traffic with a higher market penetration rate of CCAVs seems to be more efficient with respect to the one with a lower percentage of automated vehicles. For example, comparing the situation in which only the 20% of the traffic actors are CCAVs with the scenario in which CCAVs represent the 80% of the vehicles, it is possible to observe a decrease in average crossing time associated to each vehicle, that reduces from 6.27 $s$ to 4.72 $s$, with a lowering of 24%.

## VII. CAR-FOLLOWING MODELS

Car-following models describe the longitudinal interactions of vehicles on the road [100] and try to catch the way in which the driver makes decisions on how to follow the preceding vehicle efficiently and safely [101], [102].

In order to use traffic simulations to assess the level of safety associated to the developed solutions for the control and the decision-making of CAVs or CCAVs, it is very important to use a representative model of driver behaviour.

There is a huge gap between driver models for traffic simulations [91], [93], [103] and driver models that are used for active safety studies, particularly steering at relatively high lateral acceleration levels [104]. At the moment, the driver models for the two running situations are being defined in

TABLE III

KEY FEATURES OF EACH CAR FOLLOWING MODEL APPLICATION CITED

| **Reference** | **Car-following model** | **Involved parameters**<br>**Calibration procedure** | **Vehicle types and environment** | **CAVs** |
|---|---|---|---|---|
| [91] | IDM | Desired velocity, Safe time headway, Maximum acceleration, Desired deceleration, Acceleration exponent, Jam distance, and Vehicle length.<br>One-minute averages of detector data on freeways | All equal vehicles with a length equal to 5 m in freeways. | No |
| [92] | W74 | Average standstill distance (AX), additive part of safety distance (bx_add) and multiplicative part of safety distance (bx_mult). [93], [94]<br>Data track on a road section and Linear equation with Excel solver tool | Private and public city vehicles in urban arterial and express way | No |
| [95] | W99 | Standstill distance, Headway Time, Following Variation, Threshold for entering following, Negative following threshold, Positive following threshold, Speed dependency of Oscillation, Oscillation acceleration, Standstill acceleration, Acceleration at 80km/h<br>Field measurements with 20 s interval windows and genetic algorithm | Private and public city vehicles in signalised intersections | No |
| [96] | W99 | Desired speed (average) (km/h), Desired speed (standard deviation), Desired deceleration ($m/s^2$), Observed vehicles ahead, CC0 (Standstill distance), CC1 (Headway time), CC2 (Following variation), CC3 (Threshold for the entering “following”), CC5 (Positive “following” threshold), CC6 (Speed dependency of oscillation), CC7 (Oscillation acceleration), CC8 (Standstill acceleration)<br>Statistical analysis of real-world data and optimisation techniques based on genetic algorithm | Cars, trucks and cyclists in semi-two lanes roundabout | No |
| [97] | IDM | $a_{max}$ (maximum acceleration of following vehicle), V (desired speed og following vehicle), $\beta$ (acceleration exponent), $a_{comf}$ (comfortable deceleration), $S_{jam}$ (gap at standstill), T (desired time headway)<br>Data collected in the Shanghai Naturalistic Driving Study and objective function base on root mean square percentage errors | Five private light vehicles in urban express ways | No |
| [98] | W99 | CC0 standstill distance (m), CC1 headway time (s), CC2 following variation (m), CC4 negative following threshold, CC5 positive following threshold, CC6 speed dependency of oscillation, CC7 ($m/s^2$) influence of vehicle acceleration during car-following oscillation, CC8 ($m/s^2$) desired acceleration when starting from standstill, look-ahead distance<br>Vehicles simulated in VISSIM end Safety Assessment Model (SSAM) employed to extract the number of potential conflicts | Human-driven and automated light vehicles in four-way signalised intersection | Yes |
| [99] | IDM | Acceleration ($m/s^2$), Deceleration ($m/s^2$), Emergency Deceleration ($m/s^2$), delta (acceleration exponent), sigma (driver imperfection), Tau (minimum time headway), Mingap<br>Vehicles simulation and parameters retrieval in SUMO, comparing them with literature | Human-driven and automated light vehicles in four-legs single-lane roundabout | Yes |

very different manners. This is due to the fact that in the first case (traffic simulations) the driver has to interact with other drivers at a relatively low level of lateral acceleration. In the second case (active safety simulations) the driver has to cope with handling or stability problems. Obviously, a convergence is envisaged towards a holistic driver model that is still lacking.

Dealing with CAVs or CCAVs inside roundabouts, the main models used to simulate drivers' behaviour are the Intelligent Driver Model (IDM) and the Wiedemann model. For an overview of the parameters, their calibration and the environment characteristics, see Table III.

IDM [91], [105] was developed in 2000 and it is an example of a car-following model belonging to the category of the so-called ‘desired measures models’ [100]. It is featured by the account for desired values of speed and safety distance. This allows to define different traffic conditions by simply modifying the parameters involved in the definition of vehicles' behaviour: for example, it is possible to distinguish between highway and city traffic by setting different values of desired speed. The main drawback regarding the desired values of IDM parameters is the fact that they are actually unmeasurable, so their estimation is challenging because it cannot be based on direct empirical observation of traffic data. This can be a problem, especially in the case of roundabout traffic, given the complexity of the scenario.

Wiedemann's car-following model was formulated in 1974 [93] with the aim to include drivers' psychological reactions in the analysis of car-following behaviour. In particular, this model tries to take into account the fact that humans adopt strategies that are adequate rather than optimal [100], and to do so they regulate their behaviour by means of perception thresholds. The main disadvantage of this model is the fact that the various parameters in the mathematical formulation [106] are very dependent on the subjective features of the drivers involved in the measurements, in particular on driving experience. Different versions of this car-following model are used in literature, in particular Wiedemann 74 and Wiedemann 99.

An issue concerning the choice of the car-following model for simulating roundabout traffic is that it should embed a proper extent of behavioural variance. In fact, a typical driver is featured by less-than-perfect perception, decision-making process and actions [107]. To tackle this aspect, it is possible to introduce some sort of randomization function, such as in the car-following model developed by Stefan Krauss and described in [103] and in [108]. However, this model presents other problems that make it somehow not realistic, as the fact that the vehicle speed is considered as constant for each time step of the simulation, leading to a speed profile formed by a sequence of steps and to the possibility to perform the instant braking of the vehicle. A possible solution is proposed in [109], where the acceleration is considered as constant over one time step, leading to a linear piecewise speed profile. As regards the use of IDM, in [110] the variability in human driving behaviour is taken into account introducing noise on the acceleration, sampled from a uniform distribution.

As regards the movement of vehicles in a roundabout, in [111] it is studied the stability of traffic when cars are moving in a circular ring. The Authors found out that the system is stable for small and large values of the average headway, while it is unstable for intermediate values of that parameter. Moreover, for each of the stable zones, the system presents bistability: in fact, depending on the initial conditions, the system either tends to uniform flow equilibrium or to the formation of a stop-and-go wave. This phenomenon appears as a spatial wave travelling opposite to the car flow and propagating backwards along the circular road.

In any case, car-following models are featured by several parameters, that have to be calibrated in order to represent the situation as realistically as possible.

As explained by Gallelli, Vaiana and Iuele, in order to calibrate the parameters of the car-following model, it is recommended to carry on simulations of a real roundabout, both in low-traffic periods and in peak periods. In particular, in the first case in [112] the origin-destination matrix was estimated. In the second situation, the critical time gap a driver considers safe for entering the circulatory roadway was measured. The Authors used these data to calibrate the car-following model, applying Wiedemann 74 and evaluating the results in terms of mean percentage error on the average speed for the through movement. After the calibration procedure, they obtained better correspondence between the measurement collected in the real roundabout and the performances predicted by means of the simulation, especially in terms of delays and capacity.

In [96], Authors studied also the calibration process of the car-following model for traffic simulations in roundabouts with the aim to replicate conflicts of a real environment and to enhance the correlation between observed and simulated queue lengths at roundabout entries. The calibration process is based on a statistical analysis of real-world data. During the simulations, Wiedemann 99 was chosen as car-following model and the best estimates of the parameters were obtained using an optimization technique employing a genetic algorithm. Results showed that the calibration procedure affects positively the estimate of safety performance measures achieved by means of simulations, leading to more reliable outcomes. The simulation seemed to fail to reproduce forced driver manoeuvres that may cause conflicts and accidents.

In [113], Authors studied the transferability of calibrated parameters to simulation scenarios similar to the one used for the calibration, comparing the predicted queue length with the real one measured in field. They showed how the calibrated parameters are scenario-specific, as resulted also in [114], and highlighted the fact that correct transferability methodologies of the parameters from one scenario to another similar one are still to be defined.

In [97], the Authors compared the results of the calibration processes of IDM and of Wiedemann 99, showing how the latter is more difficult to calibrate with respect to the first one. In fact, IDM outperformed Wiedemann 99 in terms of mean error in calibration and validation processes and as far as it concerns standard deviation of the error in both calibration and validation phases. Moreover, with IDM there was no occurrence of collisions, which instead are present, especially in the validation phase of the Wiedemann 99 model.

The values of the parameters are different also according to the kind of vehicles involved in the simulation. In [115], a roundabout with a mixed traffic situation is studied. Two car-following models are used: conventional vehicles were modelled using Wiedemann 74 with the default parameters set in VISSIM® simulator (software for traffic simulations, [116]), while for CAVs, Wiedemann 99 was preferred, using parameters calibrated with real world-data collected in [117].

The parameters mostly affecting the calibration of the car-following model depend also on the objective taken into account. For example, in [118] the Authors carried out a sensitivity analysis on a VISSIM® simulation and found out that minimum headway distance and reduced speed of approach are vital factors for calibrating the queue length while circulating speed significantly impacts travel time. This latter quantity, however, cannot be properly calibrated, since it is not possible to assign different circulating speeds with respect to each turning movement (right turn, manoeuvre to go left, go-through straight crossing, u-turn). For both queue length and travel time, the critical gap shows a powerful contribution. Anyway, increasing the traffic volume, the simulation results become more sensitive to changes in car-following parameters.

In [98], Authors analyse the impact of the market penetration rate of CAVs. Wiedemann 99 is used for all of the vehicles, applying default VISSIM® parameters for the human-driven ones, while using the values adopted in [119] for the automated cars. The main parameters which have been reduced for CAVs with respect to conventional vehicles are the standstill distance (so the desired distance between stopped vehicles) and the headway time (i.e. the gap in seconds that a vehicle keeps from the preceding one). Assuming that connected vehicles in a platoon can accept smaller gaps compared to traditional vehicles (since they can exploit the connectivity and have information about the movements of the headway vehicles in advance), the simulation showed that penetration rate has effects both on the number of conflicts and on the delay. As regards the number of conflicts, it increases with a 25% automated vehicles penetration rate but then decreases for higher percentages (50%, 75% and 100%). As far as it concerns the delay, it decreases with the increase of connected vehicles penetration rate in case they are allowed to keep shorter headway gaps with respect to conventional vehicles. So in conclusion, in order to fully exploit the potential advantages given by the use of CAVs, the penetration rate should be quite high. One of the issues still to be tackled is the interaction between human drivers and connected vehicles, for which the use of immersive driving simulators represents a significant possibility.

In [99], Authors study the impact of automated vehicles on roundabouts, with the aim to determine the capacity of a roundabout through traffic simulations. They applied the Intelligent Driver Model to both human-driven vehicles and CAVs, but they used different parameters for the two categories of vehicles. Also in this case, the main difference regards the minimum gap between two consecutive cars, which is lower in the case of CAVs. The Authors studied the impact of the market penetration rate of CAVs on the capacity and observed that the increase in capacity is related to the increase in the amount in the percentage of automated vehicles.

As explained in [75], most of car-following models try to capture the interaction of a vehicle with the preceding one travelling in the same lane, so they have to be integrated as far as it concerns more complex situations, such as merging inside another lane. This aspect is critical when analysing vehicle movements in a roundabout, and it must be observed in depth.

In SUMO, the default settings consider at most one vehicle per lane, and consequently, lane-changes occur instantaneously. This behaviour is highly not realistic, so in order to carry on an accurate analysis of traffic situations, it must be avoided. The solution is proposed in [120], which analysed Chinese traffic and introduced the so-called sub-lane model: it is necessary to allow multiple vehicles on the same lane and allow vehicles to occupy more than one lane. To do so, the already existing lanes are divided laterally into sub-lanes, and vehicles occupy a certain number of sub-lanes, depending on their width. Two vehicles which are travelling side by side cannot occupy the same sub-lane, in order to avoid lateral collisions. With respect to the usual car-following model, with the introduction of the sub-lane model, a vehicle may have more than one immediate leader, according to which its velocity must be regulated. So in this case the car-following model takes into account all the leaders and the minimum safe speed is used, in order to avoid accidents. Also, the lane-changing model has to be modified to make use of the sub-lanes. For example, in the case of a single manoeuvre which involves more than one sub-lane, each of the intermediate sub-lanes must be checked, to prevent collisions with vehicles already occupying them. This issue must be taken into account and furtherly investigated when dealing with traffic in a roundabout. In fact, the approach of vehicles into the circulatory roadway can be seen as a merging into another lane, but there is also the possibility to have more than one lane in the circulatory roadway, so the vehicles may have to perform a lane-change manoeuvre.

## VIII. ROUNDABOUT DATASETS

This section presents the available roundabout datasets which can be used to retrieve crucial data to design and simulate the motion of vehicles into roundabouts. These datasets are very important for the introduction of automated vehicles into the roundabout. Indeed, with the available data, it is possible to precisely replicate many simulation environments and traffic conditions, increasing the capabilities of automated vehicles, and reproduce human behaviour precisely.

The rounD dataset [121] is a collection of road user trajectories that were captured at German roundabouts in a naturalistic setting. Creators employed a drone to overcome limitations from traditional traffic data collection methods, such as visual occlusion. The traffic was recorded at three distinct locations, and the trajectory and type of each road user were extracted. The positional error is typically less than 10 centimetres. This dataset can be used for various applications, including road user prediction, driver modelling, scenario-based safety validation of automated driving systems, and data-driven development of HAD system components.

Mcity's Mobility Data Center [122] is fed by real-time municipal traffic data. It aims to develop a digital infrastructure and create a cloud-based, augmented-reality CAV testbed. At the moment, two different datasets are available:

1) Roundabout Trajectory Data, created in June 2022. It is populated by vehicle trajectory data perceived from raw video frames collected by the roadside perception system;
2) Roundabout traffic conflict, created in September 2022. It is possible to retrieve vehicle trajectories and labels of the conflict events.

Five Roundabouts [123], [124] is a dataset with data about more than 23,000 vehicles as they travel through five distinct roundabouts located in Sydney, Australia. The data was gathered through the utilization of a vehicle equipped with an Ibeo [125]. HAD Feature Fusion detection and tracking system, which employs six Ibeo LUX 4 beam, 25 Hz Lidar scanners to detect road users at a distance of up to 200m. Additionally, the system has an onboard computer that allows for real-time classification and tracking.

OpenDD [126] has as its main goal to offer a valuable dataset that can enhance trajectory prediction algorithms and serve as naturalistic data for simulating other traffic participants. The dataset consists of an extensive collection of anonymized trajectories from seven roundabouts located in Wolfsburg and Ingolstadt, Germany. The dataset includes 80,000 different road users tracked with a unique object id in over 62 hours of data, as well as HD map information.

Automatum Data [127] is a smaller dataset including two roundabouts. A DJI Mavic Mini 2 drone has been used to retrieve all data. The measurement lasted about 7 minutes for both the roundabouts and tracked 64 objects travelling a total distance equal to 26 kilometres.

## IX. DISCUSSION

Despite the many contributions that have been made, the management of traffic in roundabouts when Connected and Automated Vehicles (CAVs) are present remains a significant issue. Less clear the case when CCAVs are present. There are several open questions that need to be addressed in this regard.

The behaviour of CAVs in roundabouts is often derived from that of human drivers, without considering driving comfort provided by CAVs in terms of acceleration. Vehicle dynamics models to define CAVs motion are often too simplified, thus being unable to ensure that driving control request is actually deliverable by automated vehicles. In many case studies analysed, the only controlled kinematic variable was acceleration without considering lateral and longitudinal jerks and their associated comfort effects on passengers.

Frequently, Human-driven vehicles in the network would be able to send information about their position and speed to the rest of the CAVs or CCAVs in the scenario. This assumption needs more consideration, specifically studying how such communication should take place.

Various policies for CAVs in roundabouts have been developed based on Vehicle-to-Vehicle (V2V) and/or Vehicle-to-Infrastructure (V2I) communication, emphasizing a specific configuration called V2N2V that combines the two types of communication, optimizing them and reducing the associated operation and maintenance costs for both the vehicle and the infrastructure.

Another major challenge is the development of car-following models that accurately capture the behaviour of CAVs in roundabouts. There is a need for statistical analysis to assess the variability in driver model calibration for roundabouts. Among the models analysed in this article, the IDM appears to be the best, being the easiest to calibrate and validate. For this reason, it is desirable to think that in the future this model and possibly new versions of it will be the solution used by the scientific community on the subject.

Most studies on roundabout traffic flows are theoretical, primarily due to safety concerns and cost limitations. However, the reliance on simulations for studying roundabout traffic is challenging due to the issues mentioned above regarding traffic models and the complex integration of microscopic traffic simulators with dynamic driving simulators. The use of driving simulators can provide valuable insights by incorporating human feedback in mixed scenarios involving CCAVs and human-driven cars.

In conclusion, the management of traffic in roundabouts when CAVs are present remains a challenging issue. The development of accurate driver models, the assessment of CAVs' behaviour and driving comfort, and the exploration of advanced AI schemes and cooperative decision-making algorithms are crucial for addressing these challenges. Additionally, the use of dynamic driving simulators and empirical studies can provide valuable insights into the behaviour of CAVs or CCAVs in roundabouts.

## X. CONCLUSION

A considerable amount of research work has been done to simulate the traffic flow into roundabouts when connected and automated vehicles are present. Nonetheless, a number of problems are still to be addressed and solved. The introduction of CAVs may represent an improvement in roundabout traffic, as they have the possibility to analyse the traffic environment in real-time. Traffic data can be shared together with the planned path. This leads to the opportunity to make decisions which are correct, sensible and effective in case of multi-vehicle interactions, determining the appropriate path while respecting the transportation rules. This situation would allow to increase traffic flow, safety and driving comfort. This is obtained thanks to the fact that, in principle, a connected vehicle can maintain a shorter gap between itself and the vehicle ahead, adapting its velocity according to the situation. This kind of adjustment can be repeated as frequently as it is necessary, incorporating the feedback from the actual state of the system and so smoothing the operations of the entire network. Furthermore, the reliability and the reaction time of automated vehicles are better with respect to the ones of human drivers.

In order to properly develop the geometry of the roundabout, the connection among CAVs and the traffic management algorithms, it is necessary to be able to perform reliable traffic simulations. This entails a number of problems yet to be solved.

First of all, microscopic traffic simulators, such as SUMO or VISSIM have to be employed. Both the motion of CAVs or CCAVs and human-driven vehicles have to be accurately simulated. This can be an issue if the digital twin of the connection model is not accurate enough to reproduce the time delay in the data transfer. Such microscopic traffic simulations are prone to be just a digital reproduction of reality. In order to check that an actual human would drive efficiently, safely and comfortably, in a roundabout where CCAVS or CAVs are present, at least a dynamic driving simulator would be needed. The microscopic traffic simulation software needs to be integrated into the dynamic driving simulator virtual reality environment. This proves to be an additional concern.

In any case, the behaviour of human-driven and automated vehicles must be accurately reproduced. Human-driven vehicles are implemented by considering driver models that, currently, have been derived for running mostly on highways. Consequently, the calibration of the parameters of the driver model must be tuned according to the given roundabout configuration. This seems crucial for reliable simulations.

The major problem is that the motion of automated vehicles must be provided by an optimized path management algorithm. Optimisation of traffic within the roundabout results in a trade-off between three main objective functions: traffic flow, safety and driving comfort. Communication latency is steadily an issue for any optimization algorithm. Effective and reliable communication protocols still need to be defined for CAVs. V2V, V2I or V2N2V are examples of possible communication schemes. Optimization algorithms are still in the development stage. Deep reinforcement learning policies seem to be promising. Within such policies, the most auspicious seems cooperative, model-less deep reinforcement learning. As all of the mentioned issues will be solved in the future, traffic simulations will be able to provide a cost-effective and reasonable reproduction of actual traffic. This will enable the combined design of roundabout geometry, CCAVs sensors and CCAVs path management algorithms. More than CAVs turn out to be necessary CCAVs. The latter, thanks to collaborative policies, are able to produce the most relevant results, maximising the performance of the roundabouts. Only apparently, with the current state of technology, CAVs can make the traffic in roundabouts more fluid, safe and comfortable.

## ACKNOWLEDGMENT

This work is related to the research activities performed within the AI@EDGE Project.

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Open Access funding provided by 'Politecnico di Milano' within the CRUI CARE Agreement