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Impact of Autonomous Vehicles on Roundabout Capacity

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Abstract: Studying the impact of AVs on our road infrastructure offers a lot of potential in the transportation domain; one of these issues is how capacity will be affected. This paper presents a contribution to this research area by investigating the impact of AVs on the capacity of single-lane roundabouts using a microsimulation model. For the development of the model, a roundabout situated in Győr (Hungary) was selected and field data on the roundabout geometric characteristics as well as traffic volumes were used. Simulations using Vissim were run for various scenarios based on varying input traffic volumes and market penetration rates of AVs to assess queue lengths. The highway capacity manual (HCM) roundabout model was used to estimate the capacity of the existing roundabout. Values of follow-up times and critical gaps were set to decreasing as the penetration rate of AVs increases. The results demonstrated that 20% and 40% AVs in the flow would increase leg capacities by about 10% and 20%, respectively. Furthermore, a reduction in excessive queue lengths was estimated and capacities and queue lengths were calculated by legs. It was found that these are highly influenced by the distribution of flows among legs, and the share of flows in various directions.

Keywords: roundabout capacity; autonomous vehicles; PTV Vissim; HCM capacity model

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1. Introduction

Autonomous vehicles (AVs) will have many fundamental impacts on transportation, creating new challenges for transport and network operators. Based on the literature it is expected that autonomous vehicles will improve road safety and reduce the cost of travel and emissions [1–4]. Furthermore, it is claimed that AVs will increase shared mobility and the capacity of road networks, as well.

Traffic will mainly consist of manually driven vehicles with some vehicles with automated driving functions and some AVs at the early stages of their implementation [1]. However, as AV technology rapidly advances, the share of AVs is expected to grow and their programmed behavior to evolve. This evolution will require transport operators to study the coexistence of AVs and conventional vehicles and to rethink road infrastructure standards, so they meet future needs and accommodate both types of vehicles [5,6]. Connected autonomous vehicles (CAV) are also in development. However, this paper only deals with "standalone" AVs, and does not consider V2I or V2V communication.

Researchers are interested in studying the impacts of AVs on transportation, especially the key road safety and capacity issues when AVs with different settings are mixed in traffic. This paper contributes to these concepts by examining the effect of AVs on the capacity of single-lane roundabouts using microscopic simulation in Vissim 2021 along with HCM capacity calculations. Field data of traffic volumes from an existing roundabout in Győr (Hungary) were used. The study analyzes various scenarios with different input traffic volumes as well as different penetration rates of AVs.

Roundabouts were chosen as a matter of study, as this type of intersection is more and more popular in many countries. Due to the fewer conflict points and relatively low speeds, this intersection type is safer and air pollution is also lower compared to other intersections; therefore, it has advantages regarding sustainability.

The structure of the paper is as follows. Under Section 2, a literature review is given on the capacity calculation of single-lane roundabouts as well as the expected impact of AVs. Under Section 3, data collection and methodology are introduced. Section 4 contains results, followed by limitations and discussion under Section 5. The most important conclusions are summarized in Section 6.

2. Related Research

There is a vast number of literature sources on the capacity calculation of roundabouts and a few but growing number of papers on the impact of autonomous vehicles on roundabouts. This section gives a very brief overview of the models of roundabout capacity followed by a slightly more detailed summary on the studies of AVs at roundabouts.

2.1. Roundabout Capacity

The implementation of modern roundabouts in Europe started in the 1960s. Roundabout capacities were investigated by many researchers; the tendency over the decades was that each country attempted to find its own solution [7].

Analytical models of roundabout capacity can be classified into two main groups: models based on gap acceptance theory (semi-probabilistic), and statistical models based on the regression analysis of field data (empirical). The former represents driver behavior through headway distributions of traffic on the circulating road, and critical gaps and follow-up headways of approaching vehicles [8,9]. The statistical models are regression-based methods to identify variables that determine capacity values [8,10]. Wu and Brilon recently proposed a third method for roundabout capacity calculations [10]. Their model treats the whole intersection as one entity, instead of splitting up the roundabout in several T-junctions. Compared to the usual roundabout capacity analysis techniques, their model considers the conflict points between the different types of traffic streams (vehicles and pedestrians).

One of the most widely used models is the highway capacity manual 2010 roundabout capacity model [11] updated in its 6th edition (HCM6th) [12]. It is cited under both model types above and is often cited as "a non-linear empirical (exponential regression) model with a theoretical basis in gap acceptance methodology" [8]. Researchers have also tested the adaptability of the HCM6th capacity model to local conditions e.g., [13].

2.2. Studies on AVs at Roundabouts

Cao and Zöldy, in their paper, evaluated the impact of connected and autonomous vehicle (CAV) behavior in real vehicles on vehicle fuel consumption and emission reductions [14]. They provided a preliminary theoretical summary to assess the driving conditions of autonomous vehicles in a roundabout, which attempts to explore the impact of driving behavior patterns on fuel consumption and emissions, including other key factors of autonomous vehicles to reduce fuel consumption and emissions.

A recent paper by Severino et al. focused on the evaluation of connected automated vehicles and the connected vehicles operation with the presence of pedestrians and bicycles. They simulated scenarios with zebra crossings in the main roads, positioned 20 m from circulatory carriageway edges [15].

Many researchers have examined how AVs should drive to increase safety and decrease energy demand. Wu examined the reverse concept of how intersections and roundabouts should be designed to optimize the performance of CAVs. He assessed different traffic management strategies (with cross-intersectional organization and circular organization) for CAVs under the same traffic demand at the same road junction [16].

A similar approach was taken by Lengyel et al. They suggest that CAVs should be included considering how to adapt the infrastructure to automated vehicle functions and create a seamless shift towards automated driving [17].

Calibrating the microscopic traffic simulation software for different types of AVs is one of the most challenging steps in assessing AVs' impact on traffic flow [5,6,18]. PTV Vissim software has been calibrated to simulate different types of AVs in a large body of literature that assesses the impacts of AVs on traffic flow. Researchers have calibrated PTV Vissim using a variety of methods and field data [18], as summarized in [19].

Zhao et al. [20] also used microsimulation with a simple two-way single-lane roundabout to investigate the optimal coordination of CAVs to study the effect of their penetration level on fuel consumption and travel times. Martin-Gasulla and Elefteriadou [21] addressed the same issue, namely, how to optimize the coordination of CAVs to maximize throughput and minimize average control delay. Also dealing with CAVs, Bakibillah et al. [22] developed a control system for a four-leg roundabout offering a bi-level framework, where a higher level of control forms clusters of vehicles and a lower level treats vehicles individually. Mohebifard and Hajbabaie [23] presented a method to optimize trajectories of CAVs in roundabouts.

The uniform conclusion of these studies is that with increased CAV market penetration (to nearly 100%), travel time and fuel consumption can be improved, and capacity can be increased due to the coordination of vehicles. Based on the above-cited sources it is apparent that a lot of attention has been paid to connected autonomous vehicles and slightly less to AVs. At the early stages of vehicle automation, however, there will be a coexistence of human-driven vehicles and AVs and merely the presence of AVs in traffic without being connected is worth investigating. Therefore, in this paper we focus on AVs and do not cover the possible impacts of CAVs.

3. Data Collection and Methodology

Introduced in this section are the steps we performed to study the impact of AVs on a specific roundabout where we have measured data. First, the roundabout was selected, and geometric and traffic data were collected. Then, based on these data, the model was built in Vissim. Scenarios were then defined based on the AVs penetration rates and input traffic volumes. The simulation process was performed and results were analyzed by comparing average queue lengths. Capacity calculations were made using the HCM capacity model, where critical gaps and follow-up times were defined for the scenarios.

3.1. Site Selection and Data Collection

The selected roundabout is situated in Győr (47°41′22.7″ N 17°37′27.8″ E). The city is the county seat of Győr-Moson-Sopron County and lies between three European capitals: Budapest, Vienna, and Bratislava. The selected roundabout for the study is a single lane roundabout, the most important geometric dimensions of which are given in Table 1. Figure 1 shows the roundabout along with the labels given to the four legs. All the legs have a single-entry and a single-exit lane. There is also a cycle path with crossings as well as pedestrian crossings on every leg.

Table 1. Characteristics and geometric dimensions of the selected roundabout.

Number of Legs	4
Number of Circulatory Lanes	1
Diameter of Central Island (m)	16
Diameter of Inscribed Circle (m)	35
Entry Width (m)	4.5
Circulatory Roadway Width (m)	8

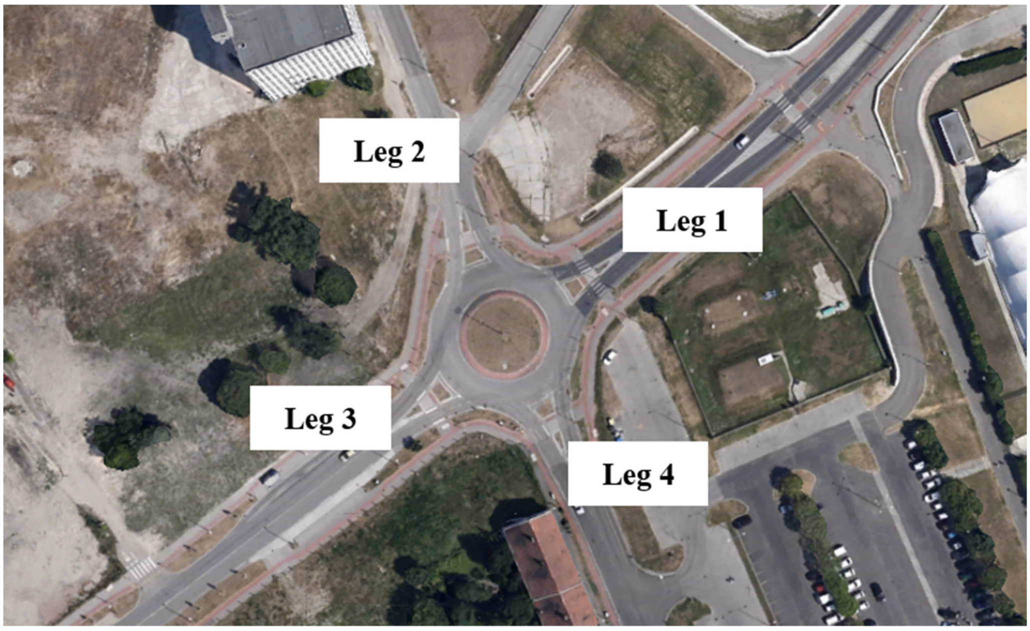

Figure 1. Labels adopted for the roundabout legs.

At the chosen roundabout, a 360-view camera (Samsung gear 360 camera) observed traffic flows and recorded traffic volume data. These measurements were done in 2019 before the COVID-19 pandemic [24], thus traffic volumes represent a normal traffic situation. The camera was placed in the center island of the roundabout, mounted at a height so that it could accurately show traffic movements on all legs as well as in the circulatory roadway. Data were recorded during morning and afternoon peak intervals (from 7 am to 8 am, and from 4 pm to 5 pm) of a normal day with good weather conditions (partly sunny, clear vision, no wind, or any weather factor that would exceptionally affect traffic flows or recording quality).

3.2. Traffic Volumes

As for traffic volume data, the total number of vehicles entering the roundabout was recorded on all the entries, and the intended exit was identified. Three types of vehicles were distinguished according to the Hungarian guideline [25] classifications:

- Light vehicles (up to 3.5 t mass: passenger cars, motorcycles, and vans).
- Heavy vehicles (above 3.5 t mass: heavy lorries and buses).
- Articulated vehicles (articulated buses and trailers).

Table 2 shows the values of factors that were used to convert the three previous items to a passenger car unit (PCU).

Table 2. Passenger car unit for vehicle type.

Vehicle Type	PCU Value
Light vehicles	1
Heavy vehicles	2
Articulated vehicles	3

Peak hour traffic volumes are given in Tables 3 and 4 below. Both peak intervals were used for the simulation in Vissim.

Table 3. Traffic volume data from 7 a.m. to 8 a.m.

		7 → 8 am				
Traffic Flow (pcu/h)		To				
		1	2	3	4	∑
From	1		74	881	13	968
	2	104		53	0	157
	3	363	19		10	392
	4	391	58	27		476
∑		858	151	961	23	1993

Table 4. Traffic volume data from 4 p.m. to 5 p.m.

		4 → 5 p.m.				
Traffic Flow (pcu/h)		To				
		1	2	3	4	∑
From	1		119	794	34	947
	2	77		87	6	170
	3	433	38		7	478
	4	498	125	37		660
∑		1008	282	918	47	2255

3.3. Roundabout PTV Vissim Set Up

The roundabout model was created from its exact background file (.dwg) considering all geometric parameters (Figure 2). The entry lanes are made long enough to accommodate traffic queuing. Pedestrian and bicycle crossings are not defined in the model, as pedestrians and bicycles are not considered at this stage of the research.

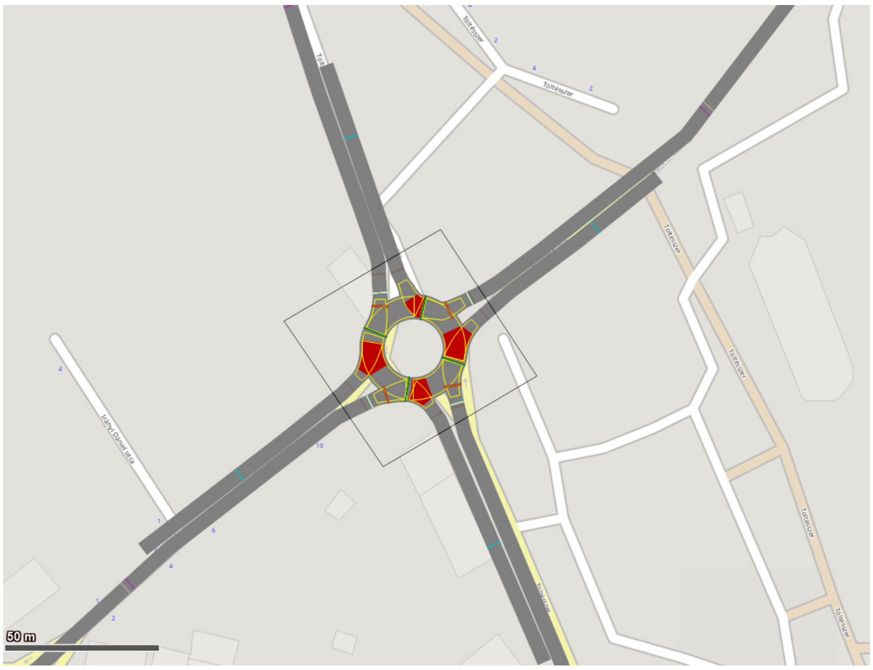

Figure 2. Modeled roundabout in PTV Vissim.

In the model, reduced speed areas are used on entry/exit legs as well as in the roundabout. Based on the deceleration parameters of the vehicles, the software automatically calculates the start point of braking, which is different for conventional versus autonomous vehicles (as well as in the three categories).

3.4. AVs and Conventional Vehicles Parameters in Vissim

Previously, several researchers have investigated the parameter settings for simulating AVs [26–29]. Zeidler et al. [26] focused on the longitudinal behavior of autonomous test vehicles and adjusted the Wiedemann car-following model parameters. They concluded that the behavior of AVs in cooperative adaptive cruise control (CACC) is modeled realistically by Vissim; however, when driving without communication the behavior is much more complicated to reproduce in the simulation. As part of the CoEXist project, Sukennik [27] provided a comprehensive description of the modeling of AVs in Vissim and gave general recommendations for the Wiedemann following behaviors. Stogios et al. [28] investigated, among others, eight car-following parameters of the Wiedemann model using the most cautious and aggressive driving extremes reported in other studies. Morando et al. [29] also used modified parameters in the car-following models, assuming more assertive behaviors for AVs.

The car-following models used in our simulations for conventional and autonomous vehicles were the Wiedemann 74 and Wiedemann 99 models, respectively. In the simulation the default values were used as illustrated in Table 5, and the parameters are described in detail in [30].

Table 5. Wiedemann 99 parameters for autonomous vehicles in PTV Vissim 2021.

PTV Vissim Parameters	Cautious	Normal	Aggressive
CC0 standstill distance (m)	1.50	1.50	1.00
CC1 gap time distribution (s)	1.50	0.90	0.60
CC2 ‘following’ distance oscillation (m)	0.00	0.00	0.00
CC3 threshold for entering ‘Following’ (s)	−10.00	−8.00	−6.00
CC4 negative speed differences (m/s)	−0.10	−0.10	−0.10
CC5 positive speed differences (m/s)	0.10	0.10	0.10
CC6 distance dependency of oscillation (1/(m·s))	0.00	0.00	0.00
CC7 oscillation acceleration (m/s^2)	0.10	0.10	0.10
CC8 acceleration from standstill (m/s^2)	3.00	3.50	4.00
CC9 acceleration at 80 km/h (m/s^2)	1.20	1.50	2.00

Vissim defines three AV behaviors labeled as cautious, normal, and aggressive. The car-following model parameters tend to reflect the differences compared to human-driven vehicles (as well as the differences among the AV behaviors); the rationale behind these parameters are as follows:

- Shorter standstill distance (CC0) and shorter safety distance (lower headway CC1 and following variation CC2), thus shorter gaps as well as shorter threshold for reaching the safety distance to a leading slower vehicle (CC3);
- Smaller values of the negative following threshold (CC4) and positive following threshold (CC5) reflecting a more sensitive reaction to the acceleration and deceleration of the leading vehicle;
- AVs can strictly follow the desired speed without oscillation, thus CC6 is set as zero;
- AVs can have more aggressive acceleration (higher CC8 and CC9).

Besides these default settings, two parameters, minimum gap time and minimum clearance, were manually set. As for the minimum gap time (time between the conflict marker and the next vehicle traveling), the values used were 3.0, 3.0, 2.9, and 2.8 s for conventional vehicles and cautious, normal, and aggressive autonomous vehicles, respectively. As for the minimum clearance (minimum distance between the conflict marker and the next vehicle traveling), these are in the same order: 22, 21, 20, and 19 m.

As the study considered single-lane roundabouts only, modeling of differences between conventional and autonomous vehicles concentrated on the yielding processes at the entry legs. In multi-lane roundabouts, the different behavior of AVs on the circulating roadway might also be a matter of interest. However, this was outside the scope of this study.

3.5. Definition of Scenarios

Using the peak hour traffic volumes, five traffic scenarios were defined where the input traffic volumes were set to 90%, 100% (baseline), 110%, 120%, and 130% of the measured values.

The rate at which AVs will enter the market, and the speed with which they will then diffuse throughout it, are both still subject to high levels of uncertainty and are particularly dependent on overcoming technological, regulatory, and legal issues, with societal acceptance of automation technology also playing an important part [2,31].

To account for this uncertainty, several different scenarios were tested to study the impact of various mixtures of manually driven vehicles and autonomous vehicles. In total, six scenarios were defined with a different market penetration of AVs (from 0% to 100%). Overall, 30 scenarios were simulated, with the six AV penetration scenarios (Table 6) combined with the five traffic scenarios.

Table 6. Tested scenarios for AVs and conventional vehicles in PTV Vissim.

Scenario	Percentage of AVs (%)	Percentage of Conventional Vehicles (%)
1	0	100
2	20	80
3	40	60
4	60	40
5	80	20
6	100	0

The authors also decided to incorporate the three AV behaviors, as follows:

- AV penetration rate of 20%: all AVs are cautious;
- AV penetration rates of 40% and 60%: all AVs are normal;
- AV penetration rates of 80% and 100%: all AVs are aggressive.

3.6. Simulation

For each defined scenario, the simulation lasted 90 min in total with the following stages: initialization (15 min), during which traffic was loaded into the road network and the system reached equilibrium; traffic simulation (60 min); and completion (15 min), where the road network emptied without disrupting the simulation stage. The simulation stages are shown in Figure 3. For each scenario, five runs with different seed numbers were performed.

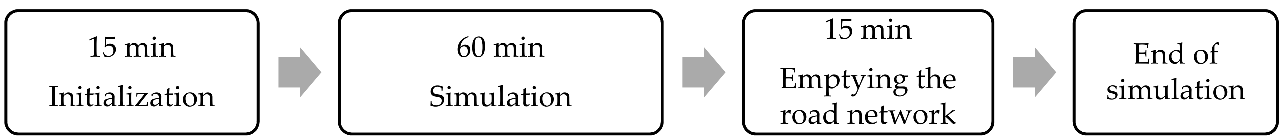

Figure 3. Simulation process.

3.7. Critical Gap and Follow-Up Time Data for HCM

The HCM capacity model requires the value of the circulation volume of a given entry; in addition, the values of t_f = follow-up headway (s) and t_c = critical gap (s) (Equation (1)).

$$C_e = A \times e^{-B \times V_c}, \quad (1)$$

where $A = 3600/t_f$, $B = (t_c - 0.5 \times t_f)/3600$, C_e is entry capacity, and V_c is circulating volume.

Currently, no available method exists to estimate the values of t_c and t_f when AVs are introduced. Due to the nature of AVs, if their percentage increases, the likelihood of shorter gaps increases. As a result, the values of t_c and t_f decrease [2,3] as the AV penetration rate increases.

In the first scenario (0% AVs), the standard values of the corresponding gap-acceptance parameters (t_f = 3.19 s, t_c = 5.19 s) provided by HCM manual are adopted. As the percentage of AVs increases, the values of t_c and t_f decrease, as illustrated in Table 7.

Table 7. Adopted values of follow-up time t_f and critical gap t_c for each scenario.

Scenario	t_f	t_c
1—0% AVs	3.19 (standard value)	5.19 (standard value)
2—20% AVs	3.00	4.80
3—40% AVs	2.70	4.20
4—60% AVs	2.40	3.60
5—80% AVs	2.10	3.00
6—100% AVs	1.80	2.40

3.8. Assumptions

Under this sub-section, the most important assumptions are summarized. A general assumption is how the programmed behavior of AVs changes with increasing penetration rates. The effect can be further evaluated with different input settings.

Discussed below are few specific assumptions related to the speeds and trajectories of vehicles, both conventional and AVs. We assumed conventional vehicles drove in the roundabout at an average speed of 30 km/h with some deviation (ranging 25–32 km/h) and they approached the entry/exit lanes at an average speed of 50 km/h (45–58 km/h).

We assumed autonomous vehicles obeyed traffic rules, e.g., before the roundabout they drive at 50 km/h and in the roundabout at 30 km/h with no deviation (desired speed).

Both conventional vehicles and AVs were assumed to drive in the middle of the lane (entry, circulatory, and exit lanes), without significant deviation. Therefore, trajectories were not considered in the simulation.

There is still no consensus on the proper car-following parameters. However, we expect rapid improvement in sensor processing technologies, high-definition mapping, and adaptive algorithms, and the deployment of I2V and V2V communication technologies will encourage companies to take vehicle automation to the next level [26,27]. As a result, highly automated vehicles will drive more aggressively [28] and this must be anticipated/reflected in the modification of car-following parameters.

4. Results

Results from the morning and afternoon intervals were similar. As afternoon traffic volumes were about 10% higher than in the morning, we show only the results for the afternoon peak. The discussion of results will first address entry capacities from different scenarios, followed by coverage of queue lengths.

4.1. Entry Capacity Results Using HCM Model

The microsimulation was performed according to the previously defined traffic configurations (scenarios). The circulating flows obtained for each scenario with increasing traffic flow percentages were used to estimate the roundabout capacity for each entry using the HCM Model. Values of t_c and t_f adopted for each scenario are illustrated in Table 7. Table 8 shows an example of AV 0% market penetration with increasing traffic volumes.

Table 8. Entry capacities [pcu/h] by legs (AV% = 0).

	Traffic Flow Percentage				
	90%	**100%**	**110%**	**120%**	**130%**
LEG1	943	924	906	888	870
LEG2	518	476	436	400	367
LEG3	1016	1004	992	981	970
LEG4	690	653	618	585	554

With increasing traffic volumes, the entry capacities are slightly decreasing. This is due to the increase in the circulating flows. As the distribution of flows among directions is uneven, the capacity decrease is also different by legs; for a 10% flow increase there is only a 2% decrease on Leg1, but an 8% decrease on Leg2. The results demonstrate that for legs with higher entry flow, the capacity reduction is lower.

The simulations illustrate the effect of AV penetration ratio where entry capacities increase for all entry legs (Figure 4). All scenarios in the figure are at 100% traffic flow percentage. The beneficial impact is greatest for the lower capacity legs; however, all legs show nearly a 2× (or better) increase. The upward curvature demonstrates the incremental benefit increases, as well. This is due to the assumed technological change, in which by increasing the percentage of autonomous vehicles, the likelihood of accepting shorter gaps increases.

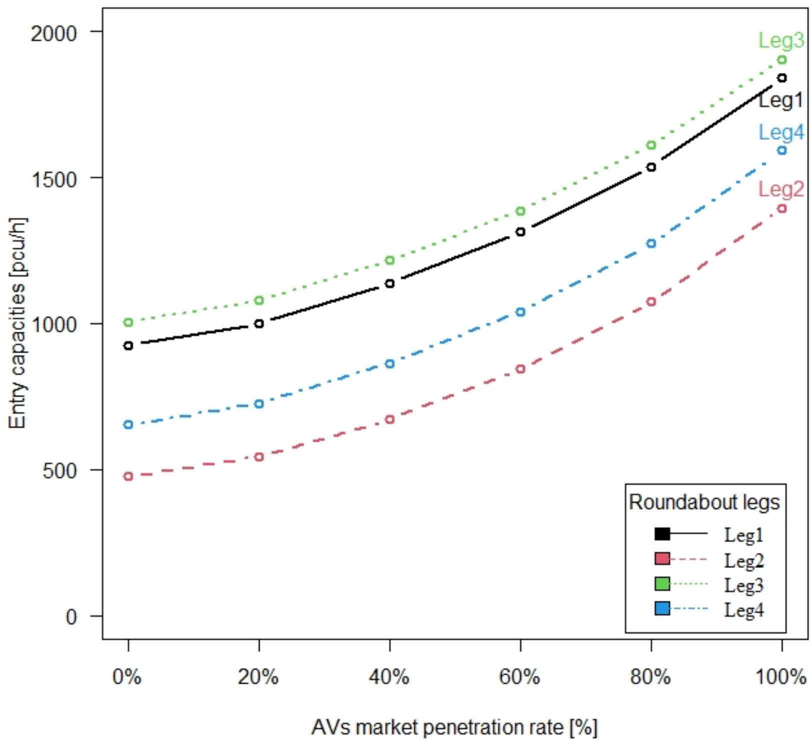

Figure 4. Entry capacities [pcu/h] by legs for different AV penetrations at 100% traffic flow level.

When using the HCM capacity estimations, the different ratios of AVs and conventional vehicles were only considered in the entry leg traffic stream, as their decision parameters are different. In the circulating traffic no distinction was made, as the entering vehicle has no information whether the vehicle in the circle is conventional or autonomous.

The results demonstrate that there are significant differences in approach capacity with different critical gap and follow-up time parameters. The approach appears to have a larger capacity with a smaller critical gap and follow-up time. For instance, comparing scenario 1 (t_c = 5.19 s, t_f = 3.19 s) with scenario 6 (t_c = 2.40 s, t_f = 1.80 s), the approach capacity for leg 1 increases by almost 50%.

The above values for entry capacities were compared to the current and expected flows, i.e., volume/capacity ratios were calculated. Table 9 shows these ratios for each leg and for the five traffic volume cases.

Table 9. Volume/capacity (V/C) ratios with increasing flow by legs (AV% = 0).

	Traffic Flow Percentage				
	90%	**100%**	**110%**	**120%**	**130%**
LEG1	0.90	1.02	1.15	1.28	1.41
LEG2	0.30	0.36	0.43	0.51	0.60
LEG3	0.42	0.48	0.53	0.58	0.64
LEG4	0.86	1.01	1.17	1.35	1.55

The calculated V/C values for the baseline case (flow = 100%, AV = 0%) are around 1.00 for Leg1 and Leg4, while under 0.50 for the other two legs. These ratios are coming from the traffic counts and HCM capacity calculations and they match well the observations of the authors that these legs in the afternoon peak are working at around their capacities.

4.2. Simulation Results for Queue Length

Average queue lengths were taken from the Vissim simulation for each leg and for the five traffic volume cases. In Table 10, the results for the AV% = 0 case are shown. In the 100% baseline scenario, the queue lengths on all legs are modest; they do not indicate problems. However, as traffic volumes grow to 110%, average queue lengths on Leg1 and Leg4 start to increase sharply to about 70–120 m (12–20 cars). However, for these two legs, the situation for 120% and 130% traffic scenarios is unacceptable. On the other hand, on Leg2 and Leg3 the situation is quite comfortable, with only a few meters queue, even when the other two legs are oversaturated.

Table 10. Average queue length [m] by legs (AV% = 0).

	Traffic Flow Percentage				
	90%	**100%**	**110%**	**120%**	**130%**
LEG1	9.6	22.6	118.5	494.6	1143.7
LEG2	1.6	2.7	4.6	7.2	9.3
LEG3	0.6	1.0	1.5	1.8	3.1
LEG4	13.2	22.6	71.9	321.0	946.4

The huge differences among the queue lengths of the legs are not simply results of the differences in entry traffic volumes. Leg1 has the highest entry volume (947 veh/h—baseline), followed by Leg4 (660 veh/h—baseline); however, the entry volume of Leg3 is about 70% of Leg4, yet the queues are much shorter on Leg3. This is due to the very uneven distribution of turning volumes and subsequent differences among circulating flows at the legs.

The results of the entry capacity calculation in Table 9 of the previous sub-chapter, and the queue length in this section (Table 10), match each other very well, although they were derived from different methods with entry flow/capacity ratios from HCM equations and queue lengths from the simulation. Saturation and queues start on Legs 1 and 4 at around the present traffic volumes, while Legs 2 and 3 could tolerate even 30% more traffic without any problems.

To study the impact of AV penetration to the queue lengths, the same five traffic volume growths and six AV penetration rates were assumed. From the four legs, only the critical Leg1 results are shown here (Table 11 and Figure 5).

Table 11. Queue length [m] on Leg1 with increasing flow at different AV penetration rates.

		Traffic Flow Percentage				
		90%	**100%**	**110%**	**120%**	**130%**
AV penetration rate	0% AVs	9.6	22.6	118.5	494.6	1143.7
	20% AVs	6.2	17.4	49.5	295.1	837.4
	40% AVs	7.0	9.9	20.6	71.1	378.4
	60% AVs	4.1	7.0	11.9	24.1	79.2
	80% AVs	2.1	3.3	6.2	10.5	18.1
	100% AVs	0.1	0.3	0.6	1.3	2.0

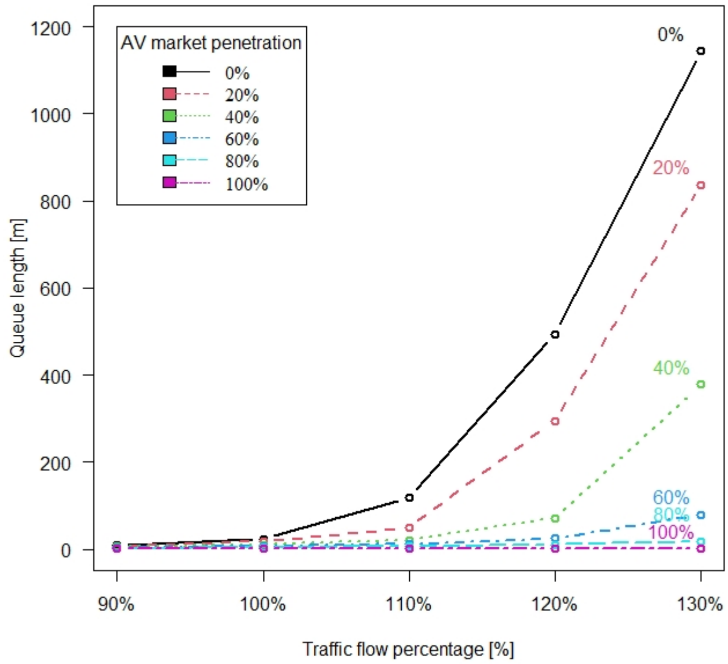

Figure 5. Queue length [m] on Leg1 with increasing flow at different AV penetration rates.

Table 11 shows that the growth of AV penetration results in decreasing queue lengths. If we look at the baseline traffic volume scenario, average queues reduce from 22 m to a few meters. However, the impact of only 20% AVs is limited at 110% traffic volume, and above 110% there are still long queues.

If we consider 20–25 m as a queue length with an acceptable level of service, it follows from Table 11 that to offset 10% growth in traffic volume from 100% to 110%, 40% AV penetration is required, while the 10% increments from 110% to 120% and to 130% can be managed by 20% AV share growth. These differences come from the assumption that as the penetration rate of AVs will increase, their capabilities will improve concerning headways and gap acceptance (i.e., their behavior will be changed from cautious to normal and aggressive).

5. Limitations and Discussion

Under this section, limitations of the study are summarized and are followed by the discussion of results.

5.1. Limitations and Credibility

As full automation of vehicles is a relatively new field, this paper has a few limitations. This study is limited to a single-lane roundabout with simplifications in terms of road users, as pedestrians and bicycles are not taken into consideration. Some aspects that are planned to affect the operation of autonomous vehicles that will enter roads in the future are not implemented in the simulations. One of these aspects is the communication between vehicles and the surrounding road network, which is a feature that will be expected at higher penetration rates. The same applies to the SAE levels, which were not considered at this stage of the research.

The car-following parameters for the various AV behaviors were default parameter values in Vissim 2021 simulations. These parameter values are regularly updated using the latest research results and were not manually changed.

The application of the HCM Model's parameters, t_c and t_f, were assumed for the scenarios and may not represent real-life scenarios. Critical gap t_c and follow-up time t_f are both important and a small change in these parameters can significantly impact capacity calculations. Today, it is not yet known how the penetration rate of AVs on our roads would impact t_c and t_f values; thus, it is expected that these important parameters will gradually decrease. Nevertheless, based on the literature and current studies, we can state that these results can be considered as reasonable estimations.

In Vissim it is possible to simulate that vehicles (conventional and/or autonomous) can spot each other and change their behavior (e.g., priority giving or following behavior and standstill distance). However, in our paper these points have not been considered.

This research estimated the impacts of AVs on roundabout capacity for various penetration levels. Different SAE levels were not considered, as these are mostly related to the width of the operational domain, while the modeled situation is a specific road element, where the increasing SAE level itself does not influence the behavior of AVs. We expect with increasing penetration rate technologies will further develop, especially concerning CAVs. Therefore, the calculated impacts can be considered as conservative estimates. However, CAVs were not considered in this research.

Finally, the paper focuses on capacity and safety is dealt with only to the extent that it is included in the simulation parameters.

5.2. Discussion of Results

The simulations give some insight into how the introduction of AVs could change capacity at single-lane roundabouts. The HCM model was used to analyze the impact of AVs on roundabout capacity. Values of follow-up times and critical gaps between vehicles entering the roundabout circulatory roadway from a queue at the entry were gradually reduced with an increasing share of AVs, resulting in increasing capacities and shorter queues. However, as autonomous vehicles (AVs) are integrated into traffic, one of the main concerns will be the perception of safety by vehicle occupants [32]. Technologically, it might be possible to adopt small gaps safely, but occupants may not accept that. Generally, people seem to accept smaller safety margins when they are in control themselves. If larger margins need to be applied to make autonomous vehicles acceptable for people, the overall traffic flow (or capacity) may get worse instead of improving [1].

Capacities and queue lengths are highly influenced by the distribution of flows among legs, and the share of flows in various directions. Most of the literature deals with the coordination of CAVs, assuming full automation e.g., [20–22]; however, less attention is paid to the effect on individual legs due to the inequalities in their traffic demand.

In this study, 30 scenarios were tested combining six AV penetration rates and five traffic growth scenarios. As for the penetration rates, the three behaviors (cautious, normal, and aggressive) were also considered, and in the capacity calculations the parameters were arbitrarily picked. Obviously, the features of these scenarios and their settings can be altered and further tested.

6. Conclusions

Based on microsimulation tools, the analysis presented in this paper demonstrates how the implementation of different levels of AVs can impact capacity at a single-lane roundabout. Vissim was used to build a microsimulation model for an urban roundabout in Hungary. An actual geometric layout and traffic data were used for model calibration.

The car-following models, Wiedemann 74 and Wiedemann 99, with default settings in Vissim 2021, were used for conventional and autonomous vehicles, respectively. Six configurations with different penetration of AVs (from 0% to 100%) and five traffic growth scenarios were considered. The HCM model was used for the capacity estimation for the individual legs by various scenarios. Values of critical gaps and follow-up times were set between 5.19 and 2.40 s and between 3.19 and 1.80 s, respectively. Both t_c and t_f are important parameters and a small change in these parameters can significantly impact capacity calculations. The results demonstrated that, with a gradual decrease in the follow-up times and critical gaps, there was a significant increase in capacity.

An important conclusion of this paper is that traffic growth and AV penetration should be studied in mutual relation. On one hand, the impacts of a certain percentage of AVs on traffic parameters (flows and queues) were estimated. On the other hand, the required share of AVs to eliminate a certain amount of traffic problems was calculated.

Another conclusion is that roundabout capacity is more than just a single number. Capacity (and other indicators, such as queue length) can be estimated/calculated by legs and are highly influenced by the distribution of flows among legs and the share of flows in various directions. This paper has presented a case study about these issues.

Future work involves simulating a wider array of scenarios and roundabout layouts and examining the interaction between vulnerable road users and AVs.

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