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Autonomous Vehicles Empty Cruising Impact on Parking Dynamics

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ABSTRACT

As development and utilization of autonomous vehicles is gaining momentum, it is expected to be decades of mixed environment where autonomous and human-driven vehicles will co-exist. Autonomous vehicles' ability to perform empty cruising can impact the parking dynamics of such a mixed environment and potentially release the parking spaces to be used by other vehicles. However, this release comes at the cost of higher vehicle kilometers travelled as the space occupation of autonomous vehicles performing empty cruising shifts from parking spaces to road spaces. Therefore, there is a trade-off between the empty cruising impact on parking search and total vehicle kilometers travelled. In this research we performed an experimental evaluation to determine how empty cruising impacts the parking search in a mixed environment in terms of frequency, duration and distance, and what is the trade-off between these changes with vehicles kilometers travelled. These key performance indicators are measured for human driven vehicles, autonomous vehicles, and also the total number of vehicles in the network to provide an in-depth insight on parking dynamics in a mixed environment. The results indicate that the fluctuation of the aforementioned key performance indicators differ based on the empty cruising duration. However, the highest impact on parking dynamics is observed at the early stages of empty cruising. Such detailed analysis of empty cruising impact on parking dynamics can enable the urban planners to better identify the optimal duration limit of empty cruising to create an equilibrium between parking demand and vehicle kilometers travelled.

CCS CONCEPTS

• Information systems → Geographic information systems.

KEYWORDS

autonomous vehicle, parking, empty cruising, intelligent transportation systems

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1 INTRODUCTION

Currently Human Driven Vehicles (HDVs) occupy a high volume of valuable land as parking spaces in cities. Autonomous Vehicles (AVs) will significantly impact the parking dynamics [2, 5, 6, 10, 13, 17], in particular by their different parking needs and parking search strategies. One of the distinctive characteristics of AVs that can transform the parking dynamics is their ability to perform empty cruising instead of (short-term) parking.

AVs ability to displace themselves from the point of arrival opens new opportunities to reduce the demand for parking spaces, and use the freed land for other purposes. However, when considering the impact of AVs on parking dynamics it must be taken into consideration that their anticipated two varieties, Shared Autonomous Vehicles (SAVs) and Private Autonomous Vehicles (PAVs), have completely different impact in such context [5]. While each SAV is believed to reduce around ten private vehicles which can substantially reduce the demand for parking spaces [4], PAVs, which are the focus of this research can compete for parking spaces similar to HDVs, or adopt other strategies including 1) looking for distant parking spaces, 2) returning home, and 3) performing empty cruising to fulfill their parking demand. A study on predicting the AVs penetration rate suggests that 25% of the vehicles will be AVs by 2045, and this number can reach to 50% penetration rate by 2050 [7]. Therefore, the focus of this research is to investigate the impact of PAVs' empty cruising on parking dynamics in a mixed environment where AVs and HDVs coexist.

Although empty cruising by PAVs can potentially release parking spaces to be used by other vehicles and reduce the number of parking searches, which we refer to as parking search frequency in this research, at the same time it can increase the total Vehicle Kilometers Travelled (VKT), which can in turn result in traffic congestion. This impact of empty cruising on parking and road occupancy can result in changes in parking search Key Performance Indicators (KPI) in terms of time spent and distance travelled compared to a full HDV environment. Therefore, when investigating the empty cruising strategy on parking dynamics, there are trade-offs among the parking search frequency, time spent and distance travelled for parking search, and the total network VKT. These trade-offs and the detailed analysis of the breakdown of their values between PAVs and HDVs, and the impact of PAVs' empty cruising on HDVs under different conditions is an existing research gap (see Section 2 for details). More specifically, we focus on addressing the following research questions.

1) How does the adoption of PAVs applying empty cruising at different rates impact the parking search frequency in a mixed environment?

2) How does the total VKT change from a HDV environment to a mixed environment, assuming empty cruising of the PAVs, and how is the difference in this VKT distributed between HDVs and PAVs?

3) How much time is spent and how much distance is travelled for the parking searches in a mixed environment?

To address the formulated research questions, an agent-based modelling approach is adopted to conduct the experimental evaluation. This approach consists of the following steps and contributions: 1) application of activity-based trip generation with varying parking demand at different time of the day for a full HDV environment to simulate real world scenario as baseline, 2) implementation and integration of empty cruising strategy of PAVs at different penetration rates in a multi-iteration experiment to investigate their impact on a mixed environment, 3) in-depth data analysis regarding the empty cruising impact on different parking KPIs including the parking search frequency, time spent and distance travelled for parking search and the total network VKT trade-off with the aforementioned parameters.

The research findings provide an insight regarding the rate of PAVs' empty cruising impact on parking dynamics in a mixed environment. The obtained data clarifies how PAVs' empty cruising strategy would improve the parking supply by freeing up the parking spaces for other vehicles and how such improvement in parking spaces demand would contribute to an overall increase of VKT. We have provided in-depth discussion on the potential implications of these insights on urban planning in terms of comprehending empty cruising behaviour and formulating policies to create an equilibrium between total network VKT and frequency of parking searches in preparation of adopting PAVs in cities of future.

2 LITERATURE REVIEW

Parking spaces management is one of the main challenges in urban planning where high amount of valuable lands are allocated to parking spaces in major cities. In Europe the amount of land occupied by parking spaces is at least half of entire land area of Belgium and in USA is as large as state of Massachusetts [8]. There have been various efforts from both researchers and urban planners to optimize the parking dynamics and facilitate parking search. These efforts focus on various spatiotemporal factors including parking prices [9, 16], parking spaces' spatial distribution [4], car sharing to reduce the number of vehicles on the road [14], public transport to reduce the parking demand, and restrictions on parking duration [16]. Nevertheless, parking dynamics management remains one of the major challenges due to urbanization and increasing number of vehicles. Emergence of AVs and their characteristics differences with HDVs from parking search perspective can provide potential solutions to improve parking dynamics.

AVs are expected to be present on roads between 2027 to 2035 and will become widespread between 2040 to 2050 [7, 12]. Due to the existing challenges in integrating AVs into existing HDV environment, there can be decades of mixed environment where AVs and HDVs would co-exist and compete for using urban transport

infrastructures including parking spaces. Extensive technological development, initial high costs of AVs, limited production scale, cities' infrastructure transformation, social acceptance, and policies and regulations refinements are some of these challenges [3, 19]. In such a mixed environment, AVs not only can compete for nearest parking spaces similar to HDVs but also have the capability to adopt different strategies to address their parking demand including 1) looking for distant parking spaces, 2) returning home, and 3) performing empty cruising. When empty cruising is selected as the strategy to address the parking demand of PAVs, a trade-off between parking search frequency and total network VKT is created where PAVs will either occupy parking spaces or the road spaces. Therefore, when discussing the parking dynamics in the age of AVs, the VKT is a critical parameter to consider in such context [12]. PAVs empty cruising has created a potential research area, however analysis of the existing literature shows that only a limited number of studies specifically focus on this strategy from various perspectives which are addressed in the following section.

Bischof et al. [2] focused on parking search for PAVs and simulated three different degrees of PAVs utilization (0%, 10% and 20%) by population. For 10% and 20% degree of utilization they consider three strategies taken by PAVs which are a) conventional parking search for nearest free spot, b) parking at an AV lot and c) empty cruising. They argue that parking at a designated AV lot results in lowest parking search duration and at the same time would control the impact of PAVs on increasing VKT and traffic congestion. However, another study suggests that since PAVs can perform empty cruising to look for distant parking spaces, they usually travel in outbound directions in peak hours of the day where the traffic bottleneck capacity is large enough and would not significantly impact the traffic congestion [17]. Millard-Ball [13] conducted research on the impact of PAVs on parking spaces and also the traffic congestion. In this research three strategies for parking search are adopted by PAVs which are empty cruising, returning home, and looking for distant parking spaces. When addressing the empty cruising behaviour of PAVs, he argues that PAVs can potentially blur the boundary between parking and travel where they can travel with minimum speed to avoid parking fees and also consuming less energy. This means AVs can potentially create traffic congestion on purpose through empty cruising. As a result, applying tolls on empty cruising in the age of AVs seems inevitable [15]. Fagnant and Kockelman [4] focused on the PAVs penetration rate and their impact on total VKT. They suggest that at a 10% market penetration rate, the VKT per PAV will be 20% higher compared to HDVs, whereas at a 90% market penetration rate, the VKT per PAV is expected to be 10% higher than HDVs. This indicates that the ratio of PAVs to HDVs population is a fundamental parameter to consider when analyzing the VKT impact of PAVs empty cruising. Another study, by Harper et al. [6], analyzes the PAVs' impact on VKT, and shows that at low penetration rates (5%–25% AV penetration), PAVs would travel an additional 5.6–6.4 km per day, and at high penetration rates (50%–100% AV penetration) PAVs would travel an additional 11.8–13.4 km per day compared to 0% penetration rate.

Some studies suggest that PAVs' empty cruising creates an opportunity to transform the spatial distribution of the parking infrastructures to other zones on urban fringe areas [10, 18]. However, when considering such scenario, multiple parameters such as VKT,

travel cost of PAVs, traffic congestion and parking pricing must be taken into consideration. These research findings indicate that in such scenario to control the network congestion there must be varying amounts of parking and congestion toll during different times of the day when parking demand is different. Such approach is only rational for parking spaces which are dedicated for AVs with Vehicle to Vehicle (V2V) and Vehicle to Infrastructure (V2I) capability since constant change in parking prices or congestion toll in a day can be confusing for human drivers [20]. Alekszejenkó and Dobrowiecki [1] considered auction-based parking as a solution to control the empty cruising of PAVs in a fully autonomous environment. They propose an approach by which municipalities provide auction-based parking lots where PAVs can bid based on the parking price and their travel cost to reach the parking space. They argue that this approach can provide a potential solution to optimize the parking allocation for PAVs and creating an equilibrium between parking price and VKT.

Although the conducted research on analysing the PAVs empty cruising provides valuable insights regarding the parking dynamics in the age of AVs, an evaluation regarding (a) the trade-offs between parking searches (in terms of frequency, duration and distance) and the VKT in a mixed environment where PAVs perform empty cruising at different population and duration rate and (b) a breakdown analysis regarding the HDVs and PAVs contribution to these KPIs to clearly understand the impact of empty cruising on HDVs is missing in existing literature. Therefore, in this paper we focus on addressing these research gaps.

3 METHODOLOGY

The experiment to address the formulated research questions in this paper is conducted using Simulation of Urban Mobility (SUMO) [11]. SUMO is an activity-based microscopic and continuous traffic simulation application which has integrated parking search modules. Although currently there is no module for AVs integrated in SUMO, it is an open source application, enabling us to develop modules to generate vehicles with different behaviours such as AVs with empty cruising strategy. In this section, the experiment environment and process are discussed in detail.

3.1 Experiment Environment

The environmental attributes of this research experiment include the road network, vehicles, and synthetic population to generate activity-based trips in the network.

Road Network: For this research, a simple grid-based road network is utilized. The rationale behind simplifying the road network is to facilitate the modification and execution of various iterations of the experiment. Additionally, it enables a better comprehension of the impact of different vehicle types on parking dynamics within a controlled and traceable environment. Figure 1 illustrates the road network.

The network consists of 26 streets which are divided by junctions presented in Figure 1, adding up to a total of 10.7 km road length. There are 52 parking areas with total of 600 parking spaces capacity distributed across the network where each street has one parking area on each side. The capacity of parking areas varies based on the road type. There are four distinct road types, each characterized by

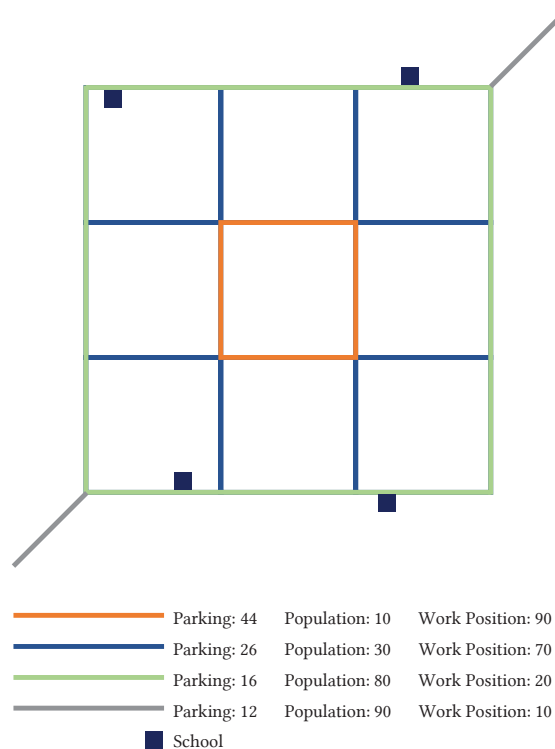


Figure 1: Experiment road network with parking spaces, population density, workplaces and schools distribution.

varying numbers of parking areas spaces, population density, and work distribution which are depicted in Figure 1. This configuration allows for the simulation of a Central Business District (CBD) situated in the middle of the network, where a higher volume of work-related trips are expected during the early hours of the day. There are also four schools in the network, which are in the suburb areas illustrated in Figure 1.

Vehicles: In this experiment two different vehicle types are used, which are as follows:

- **Human Driven Vehicles (HDVs):** This vehicle type looks for the nearest parking space to their destination. It then remains in the parking space for the allocated period of time and then returns home.
- **Private Autonomous Vehicles Applying Empty Cruising (PAVECs):** This vehicle type looks for the nearest parking space to the destination to drop the passenger, it then performs empty cruising on the road for the allocated period of time and subsequently returns to the drop point location, looks for a parking space to pick up the passenger, and returns home. PAVECs trigger two parking events during

their trip in the network for dropping and picking up the passenger before and after empty cruising.

Synthetic Population: In total 400 households have been allocated to the road network which include 2500 inhabitants. These households represent a demand of 2000 trips in a single day to work and schools. The distribution of population, workplaces and schools are illustrated in Figure 1.

3.2 Experiment Process

The experiment in this research is a multi-iteration experiment where in each iteration different number of HDVs and PAVECs are deployed in the network to analyze the parking dynamics. The experiment duration is 24 hours where each second is considered as one step in the simulation application. The spatial distribution of the vehicles throughout the day is based on the workplaces and schools positions (illustrated in Figure 1) and the temporal distribution is based on the work hours (opening at 8:30 to 9 am and closing at 17:30 to 18 pm) and school hours (opening at 8:30 am and closing at 15:30 pm).

Parking Search Strategy: The parking search strategy for all vehicles is to find a parking space in the same street (parking area) where the destination is located. If no empty parking space is available in the same street as destination, then the vehicles look for the nearest parking area on opposite side of the street or adjacent streets. When a parking area is visited and marked as full by the vehicle, it will not be revisited for the next 10 minutes which is the default value in SUMO simulation. This process of parking search continues until the vehicle locates a parking space. Once the parking space is found, the HDVs will remain in the parking space whereas PAVECs perform a short stop under 60 seconds to drop the passenger. The PAVECs then perform empty cruising by circulating in the shortest path in respect to their destination point until their empty cruising duration finishes. Subsequently, PAVECs perform another parking search with less than 60 seconds stop time to pick up their passenger and returning home.

Parking KPIs: In addition to parking search frequency, the time spent and distance travelled for parking search and also the total network VKT is measured. In this research we define these KPIs as follows:

- **Parking Search:** The event when a vehicle reaches to its destination and cannot find any parking spaces in the same street and looks for parking in adjacent streets or on the opposite side of the street.
- **Parking Search Duration:** The time it takes for the vehicle to complete the parking search in seconds.
- **Parking Search Distance:** The distance travelled by vehicle to complete the parking search in meter.
- **VKT:** The total distance travelled by all vehicles in their entire trips.

Simulating PAVECs: The above mentioned KPIs are then used to analyze the impact of adopting PAVECs at different population and duration rate on parking dynamics. In this research we analyze the conversion of short-term parking demands of up to 30 minutes to empty cruising in three iterations. In Iteration 1 of the experiment only HDVs are used to determine how many parking searches are conducted in a fully HDV environment. In Iteration 2, 200 HDVs

(10% of the original population) with parking duration up to 10 minutes are converted to PAVECs. In Iteration 3, another 200 HDVs, with parking duration between 10 to 20 minutes, are converted to PAVECs, and finally in Iteration 4 another 200 HDVs with parking duration between 20 to 30 minutes are converted to PAVECs. This distribution of PAVECs with different empty cruising duration as illustrated in Figure 2 enables an in-depth analysis of the impact of adopting empty cruising strategy to address short term (up to 30 minutes) parking demands. The other 70% of HDVs which have parking demand between 30 minutes to 8 hours remain the same in the entire experiment. As discussed previously in the experiment environment section, each PAVEC will have one more parking event compared to HDVs, therefore although the number of vehicles are constantly fixed in all iterations of the experiments, the number of parking events changes based on penetration rate of PAVECs. Figure 3 illustrates the number of parking events at different iterations of the experiment.

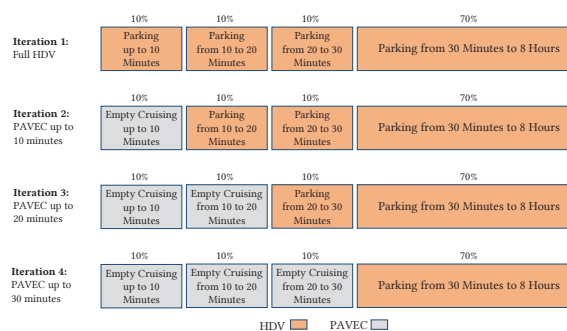


Figure 2: HDVs' parking duration and PAVs' empty cruising duration distribution ratio across 2000 trips in each iteration of the experiment.

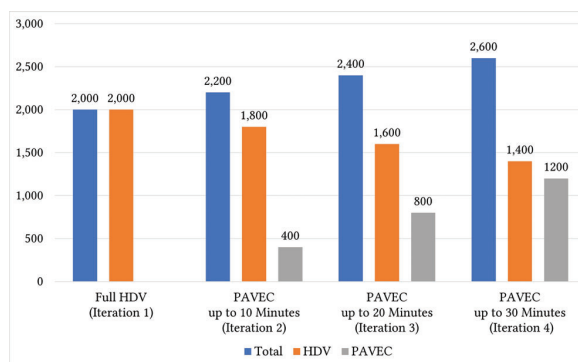


Figure 3: Number of parking events at 0%, 10%, 20% and 30% empty cruising penetration rate with one parking event for HDV and two parking events for PAVEC vehicle types.

Assumptions: The following assumptions are made in the experiment.

- 1) All parking spaces are public and can be used by all different vehicle types.
- 2) There is no parking cost.
- 3) All vehicles will persistently search for available parking spaces until they locate one.
- 4) The PAVEC return to the same location where they dropped the passenger and look for the nearest parking space to pick up the passenger.
- 5) All vehicles only perform one trip in the network and return home.

4 RESULTS

In order to address the formulated research questions in Section 1, in this section the findings of the experiment are analyzed using the four aforementioned KPIs namely 1) parking search frequency, 2) network VKT, 3) parking search duration, and 4) parking search distance. Since the HDVs are incrementally converted to PAVECs in each iteration of the experiment (200 per iteration), therefore the analysis of each iteration impact on parking dynamics is performed in an iteration-wise format, where each iteration output is compared with the previous iteration. In addition, since the population of HDVs and PAVECs change in each iteration, therefore the average value for the parking search duration, parking search distance, and VKT KPIs, which are calculated based on each vehicle type population in each iteration, are used for data analysis. This approach helps to provide an accurate iteration-wise breakdown analysis where the impact of empty cruising on parking dynamics is investigated.

Since empty cruising is a continuous process, which means in each iteration PAVECs will have variable empty cruising duration, there is a trend line for each KPI over the entire 30-minute empty cruising period (from the beginning of Iteration 2 to the end of Iteration 4). To identify this trend line, a polynomial interpolation is used to estimate the continuous values of the KPIs in the entire 30 minutes of empty cruising. To enhance the accuracy of interpolation process, in addition to the four initially obtained data points at 0, 10, 20 and 30 minutes of empty cruising, three additional data points in the middle of each iteration time span at 5, 15, and 25 minutes were also obtained through the simulation. Subsequently these seven data points were used to identify the trend line of the KPIs for entire empty cruising duration across all iterations. Such analysis enables a more profound understanding regarding the empty cruising impact on the KPIs at any given point of time and accurately identifying the points which have the highest impact on each KPI.

In the following sections the impact of empty cruising on each KPI and the correlation between them is discussed in detail.

4.1 Parking Search Frequency

To formulate a KPI to analyze the parking search phenomena for addressing the Research Question 1, in this experiment a parking search is defined as the event when a vehicle reaches to its destination and cannot find any parking spaces in the same street and looks for parking in adjacent streets or on the opposite side of the street. Table 1 shows the parking search frequency in different iterations of the experiment for HDVs, PAVECs, and also the total for both vehicle types. In addition, it shows the parking search frequency

ratio to total number of trips (Figure 2) and parking events (Figure 3). Although the number of trips and number of parking events are equal for HDVs where each HDV only looks for a parking space once in each trip, but as shown in Figure 3, each PAVEC will trigger the parking event twice in its trip which is one for the dropping and one for picking up the passenger. Therefore, for analyzing the parking search KPI, we focus on the parking searches ratio to total number of parking events in each iteration.

As it can be noticed from Table 1, in a full HDV environment 685 parking searches were performed, which is 34.3% of entire parking events. In Iteration 2 where 10% of vehicles are allowed to perform empty cruising the total parking search frequency is 676 which is relatively constant compared to Iteration 1. However, when considering the ratio of parking search frequency to number of parking events, Iteration 2 results in 3.6% reduction for both total and HDV parking searches as shown in Table 1.

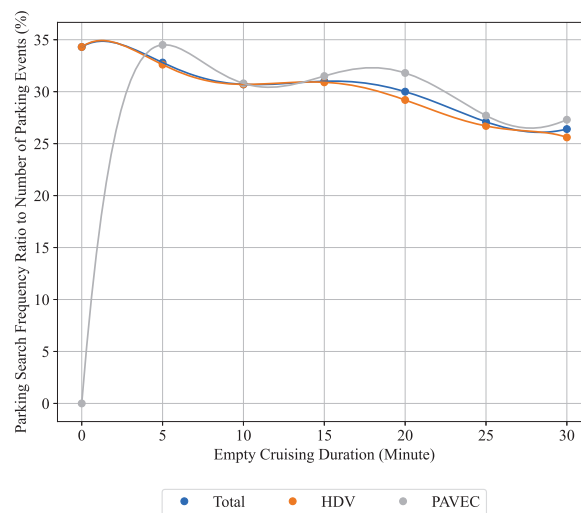


Figure 4: Polynomial interpolation trend line of parking search frequency ratio to number of parking events showing two major drop points in Iterations 2 and 4.

This data shows that the amount of parking release by PAVECs outweighs the impact of one additional parking event per trip by these vehicles. In Iteration 3, the total parking search frequency is increased by 45 compared to Iteration 2, however when considering the ratio of this number to parking events there is 0.7% reduction. Iteration 3 also improves the parking search for HDVs by 1.5% reduction. Although in Iteration 3 the parking search ratio for PAVECs is increased by 1.0%, however in Iteration 4 where 30 minutes of empty cruising is allowed a significant reduction in parking ratio for all the vehicles is observed. In Iteration 4, the parking search ratio is dropped by 3.6%, 3.6% and 4.5% for total, HDVs and PAVECs respectively. The application of polynomial interpolation to investigate the pattern of empty cruising impact on parking search frequency is illustrated in Figure 4. This figure shows that the total and HDVs parking search ratio follow a similar

Table 1: Parking search frequency and its ratio to total number of trips and parking events.

	Full HDV			PAVEC up to 10 minutes			PAVEC up to 20 minutes			PAVEC up to 30 minutes		
	Total	HDV	PAVEC	Total	HDV	PAVEC	Total	HDV	PAVEC	Total	HDV	PAVEC
Parking search frequency	685	685	NA	676	553	123	721	467	254	686	359	327
Parking search frequency ratio to total number of parking events	34.3%	34.3%	NA	30.7%	30.7%	30.8%	30.0%	29.2%	31.8%	26.4%	25.6%	27.3%
Iteration-wise fluctuation of parking search frequency ratio to total number of parking events	NA	NA	NA	-3.6%	-3.6%	NA	-0.7%	-1.5%	+1.0%	-3.6%	-3.6%	-4.5%

pattern as empty cruising time increases. There is one major drop point in parking search frequency at 5 minutes of empty cruising and after that at around 15 minutes of empty cruising duration the reduction of parking searches noticeably reduces. However as the empty cruising time is extended to 30 minutes another major drop point is noticed at 25 minutes with similar impact of the first major drop point at 5 minutes. In overall Figure 4 shows that as the duration of empty cruising increases in the given environment, the parking search frequency reduces compared to full HDV environment where at the end of Iteration 4 the total and HDV parking searches are reduced by 7.9% and 8.7%. However, the ratio of such reduction fluctuates at different empty cruising times where at 5 minutes and 25 minutes highest reduction are observed and at 15 minutes the impact of empty cruising on parking searches reaches an equilibrium. This equilibrium point at 15 minutes in Iteration 2 is significantly important to make decision on allowing optimal time of empty cruising in a network. Although Iteration 4 shows significant impact on reducing the parking search similar to Iteration 2, however it is necessary to note that the cost of such reduction of parking searches is significantly higher in iteration 4 since the total road network occupation by PAVECs is much longer and significantly more VKT is enforced on the network load compared to Iteration 2. Therefore, it is remarkably important to analyze the impact of empty cruising duration on total network VKT which is addressed in the following section.

4.2 Vehicle Kilometers Travelled (VKT)

Although the obtained data shows that empty cruising can potentially have positive impact on parking dynamics in terms of parking search frequency, but there is a trade-off between this improvement and additional VKT imposed on the network by PAVECs. Therefore, in this section we focus on Research Question 2 regarding the total change in VKT and how the change in this KPI is distributed between HDVs and PAVECs in each iteration. When PAVECs perform empty cruising they would increase the total VKT, however understanding the rate by which such increase occurs enables to determine the optimal empty cruising duration by urban planners.

As it can be noticed from Table 2, as the duration of empty cruising increases by 10 minutes in each iteration, the VKT rate increases exponentially. The results show that Iterations 2, 3 and 4 increase the average VKT for all the vehicles by 27, 765 and 1,268 meters respectively compared to Iteration 1. Considering the distribution

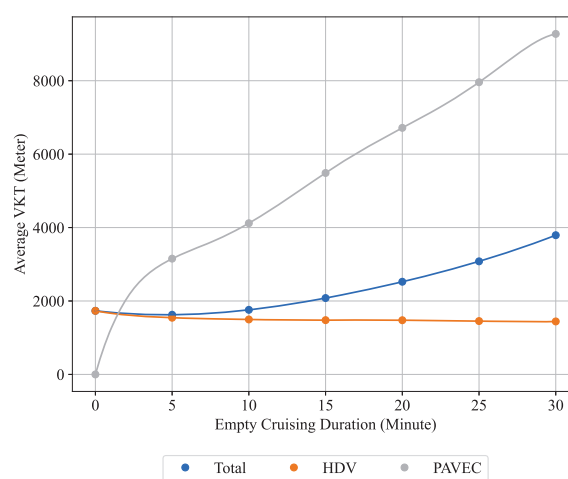


Figure 5: Polynomial interpolation trend line of average vehicle kilometers travelled showing minor fluctuation in Iteration 2 and exponential increase in Iteration 3 and 4.

of average VKT change between HDVs and PAVECs, the observed data shows that in Iteration 2 there is a significant reduction of average VKT for HDVs, which is 235 meter. However, this impact reduces to 21 and 33 meters for Iteration 3 and 4. This reduction rate for HDVs' average VKT in Iteration 3 and 4 is remarkably low compared to the increase of PAVECs' average VKT. Iteration 3 and Iteration 4 show 2,598 and 2,559 meters increase in average VKT for PAVECs respectively. The illustrated result of a polynomial interpolation in Figure 5 shows that at 10 minutes empty cruising duration, the average VKT in entire network is relatively similar to a full HDV environment, while the average VKT for HDVs is significantly reduced in this iteration. This indicates that the reduction of parking search frequency discussed in Section 4.1 compensates for additional VKT by PAVECs when performing empty cruising up to 10 minutes. Therefore, in such environment HDVs benefit from both reduction of average VKT as well as the parking search frequency. As previously shown in Figure 4, there were two major drop points in parking search frequency at 5 and 25 minutes of

Table 2: Total and average vehicle kilometers travelled

		Full HDV			PAVEC up to 10 minutes			PAVEC up to 20 minutes			PAVEC up to 30 minutes		
		Total	HDV	PAVEC	Total	HDV	PAVEC	Total	HDV	PAVEC	Total	HDV	PAVEC
Average VKT (Meter)		1,732	1,732	NA	1,759	1,497	4,118	2,524	1476	6,716	3,792	1,443	9,275
Iteration-wise fluctuation of average VKT (Meter)		NA	NA	NA	+27	-235	NA	+765	-21	+2,598	+1,268	-33	+2,559

empty cruising, however analysis of the average VKT show that the first point at 5 minutes empty cruising results in significant reduction of parking searches without increasing the average VKT. In fact the interpolation analysis in Figure 5 shows that at 5 minutes empty cruising there is a reduction of 107 meter in average VKT compared to full HDV environment before reaching to a 27 meters increase at 10 minutes of empty cruising. Although, the second drop point for parking searches at 25 minutes empty cruising creates a similar impact on parking search frequency as the first drop point at 5 minutes of empty cruising but it comes with a cost of 1,455 meters increase on average VKT. This data indicates that based on the parking demand in a network, there is an equilibrium point where the parking search frequency reduction compensate for increase of VKT by PAVECs. Once this point is reached any longer duration of empty cruising only imposes higher VKT on the network without significant improvement on parking dynamics. This signifies the importance of imposing limitation on empty cruising duration by urban planners by considering the spatiotemporal characteristics of parking demand across the city zones and at different times of the day.

4.3 Parking Search Duration and Distance

When considering the impact of empty cruising on parking search frequency, each parking search can have varying duration and distance. Therefore, the reduction of parking search frequency does not necessarily indicate the improvement of parking dynamics. As a result, to address the Research Question 3 we focus on the duration and distance KPIs for parking searches in different iterations of the experiment. Regarding the average parking search duration, Table 3 shows that in Iteration 2, when 10 minutes of empty cruising is allowed, the average parking search duration is 209 seconds, which is 35.4% higher compared to full HDV environment with 135 seconds. In Iteration 3, the average parking search duration decreases to 103 seconds and drops below the value of full HDV environment by 32 seconds which is equal to 23.7% reduction. Iteration 3 shows the highest iteration-wise reduction on average parking search duration for total, HDVs and PAVECS by 106, 113 and 126 seconds reduction respectively. The reduction of average parking search duration trend continues in Iteration 4 where 46 seconds reduction is observed total trips. Comparing to full HDV environment, Iteration 4 shows 78 seconds or 57.7% reduction in average parking search duration. As it can be noticed in Figure 6, although the results analysis in previous sections show that Iteration 2 had the best impact on parking search frequency and the

VKT, when considering the parking search duration this iteration is the only iteration which has higher value compared to full HDV and vehicles spent more time in this iteration for parking search compared to other iterations.

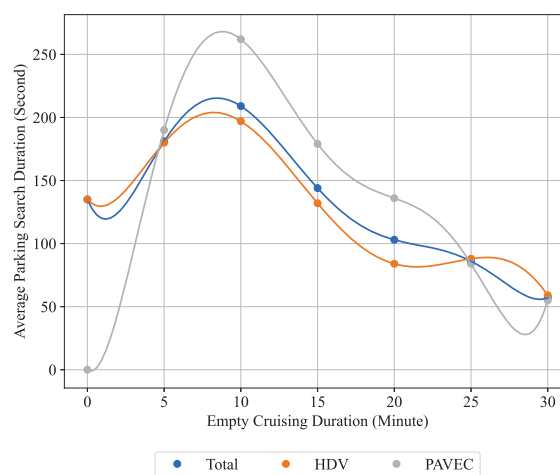


Figure 6: Polynomial interpolation trend line of average parking search duration showing significant increase in the initial stage of empty cruising.

The analysis of parking search distance shows a contrasting outcome compared to parking search duration. Although regarding the duration, Iteration 2 has adversely impacted the parking search duration and remarkably increased it, but in respect to distance, Iteration 2 has the highest positive impact on the distance travelled for parking search. As Table 3 show, Iteration 2 significantly reduces the average parking search distance travelled from 1205 meters to 523 meters which shows 56.5% reduction. The trend line in Figure 7 indicates that the major drop in average parking search distance is at around 5 minutes of empty cruising where highest reduction in parking search frequency was also observed. Iteration 3 and Iteration 4 also continuously reduce the parking search distance however their impact is remarkably less than Iteration 2 impact on these KPIs. This indicates that although increasing the empty cruising duration up to 30 minutes constantly reduces the parking search distance but the major impact is at 5 minutes empty cruising

Table 3: Total and average parking search duration and distance.

	Full HDV			PAVEC up to 10 minutes			PAVEC up to 20 minutes			PAVEC up to 30 minutes		
	Total	HDV	PAVEC	Total	HDV	PAVEC	Total	HDV	PAVEC	Total	HDV	PAVEC
Average parking search duration (Second)	135	135	NA	209	197	262	103	84	136	57	59	55
Iteration-wise fluctuation of average parking search duration (Second)	NA	NA	NA	+74	+62	NA	-106	-113	-126	-46	-25	-81
Average parking search distance (Meter)	1205	1205	NA	523	500	629	464	436	515	330	341	319
Iteration-wise fluctuation of average parking search distance (Meter)	NA	NA	NA	-682	-705	NA	-59	-64	-114	-134	-95	-196

duration and after this point of time the ratio of empty cruising impact on parking search distance significantly reduces.

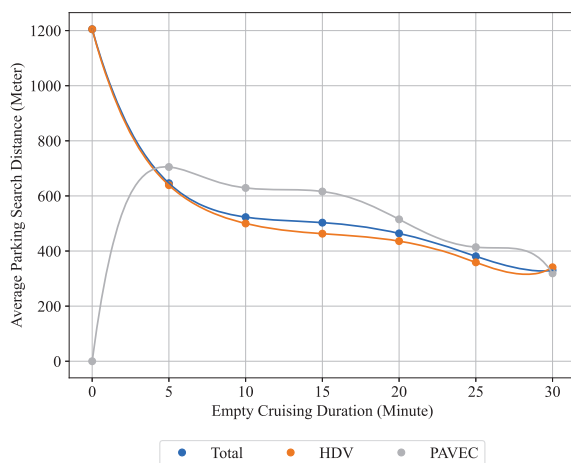


Figure 7: Polynomial interpolation trend line of average parking search distance showing more than 50% reduction in the initial stage of empty cruising in Iteration 2.

5 DISCUSSION

In this section we discuss the presented research from the perspectives of research remarks, implications on urban planning policies and the research limitations.

5.1 Research Remarks

The experiment observations in the given environment show that empty cruising strategy will instantly impact parking search KPIs at early stages of empty cruising duration. The interpolation analysis

shows that once the empty cruising duration reaches to 5 minutes in Iteration 2, the parking search frequency (Research Question 1) and also the parking search distance (Research Question 3) significantly reduce while at the same time the total VKT (Research Question 2), which is expected to increase, is also slightly reduced compared to full HDV environment. The only KPI which is adversely impacted at 5 minutes of empty cruising is average parking search duration (Research Question 3) which is higher than full HDV environment. The reduction of VKT and parking search distance at this point indicates that the increase of parking search duration is occurred due to the traffic congestion caused by PAVECs. In Iteration 2 where only 10 minutes of empty cruising is allowed, PAVECs will quickly return to their initial destination to compete for the second parking event to pick up their passenger and therefore cause congestion. However, as the empty cruising duration increases, the higher number of parking release compensates for the impact of PAVECs second parking search event on parking search duration and this KPIs starts to decline. So, while parking search frequency and parking search distance KPIs constantly decrease throughout the experiment, parking search duration experience an increase in Iteration 2 before starting to reduce and network VKT experiences a decrease in Iteration 2 before starting to increase. This trend shows that the trade-offs change at different duration of empty cruising where at early stages there is a trade-off between parking search duration and other KPIs and after passing the 10 minutes empty cruising point this trade-off shifts to a trade-off between VKT and other KPIs.

5.2 Implications on Urban Planning Policies

The research findings indicate that the decision to select the optimal duration for allowing empty cruising by urban planners will depend on the existing network congestion and parking occupancy rate in a fully HDV environment. When making such decision it must be considered that how much parking spaces is required to be released to reach an optimal point of parking occupancy rate and at the same time how much increase of road usage by PAVECs can

be accommodated in the existing road network before reaching a congested state. In addition, when considering the impact of empty cruising on VKT, as long as the increase of VKT does not cause traffic congestion, the cost of empty cruising is individual and mostly affects the vehicles owners, however when empty cruising causes traffic congestion it will impose a collective cost on the entire road users who are in the congested area and therefore the improvement on parking dynamics can be substantially undermined by the imposed collective cost of traffic congestion. This shows that the direction of empty cruising can also play a potential role in determining the optimal empty cruising duration by urban planners, where longer empty cruising can be allowed in outbound directions. This approach can potentially help to direct the PAVs to perform their empty cruising in opposite direction of HDVs normal traffic flow and therefore reduce their VKT impact on HDVs while at the same time releasing the parking spaces for HDVs to be used. Since these parameters can fluctuate at different times of the day and also across different geographical locations in the city, there will be a need for applying variable-rate empty cruising duration permission in different city zones and at different times of the day. AVs' capability to have V2I and V2V communications facilitates such variable-rate empty cruising strategy since these vehicles can be constantly updated regarding the latest changes. This helps to optimize the empty cruising strategy and create an equilibrium between parking searches and total network VKT.

5.3 Research Limitations

There are several limitations in this research experiment that addressing them can potentially impact the existing findings. The first limitation is that multi-leg trips are not simulated in this experiment and each vehicle only makes a single trip with one parking event for HDVs and two parking events for PAVECs. The second limitation is that the impact of other means of transport including bicycles, taxis, buses and trams on parking dynamics and traffic flow is not considered in this experiment. Moreover, due to limited computational resources the traffic flow was limited to 2000 trips in a relatively small grid network, however conducting a research with varying number of trips, network typologies, parking layouts and congestion levels can result in a more in-depth perception of empty cruising impact on parking dynamics and network VKT. Nevertheless, since in this research all the HDVs and PAVECs were deployed under similar circumstances, it creates a reliable outcome regarding the empty cruising impact on parking dynamics and total network VKT. Such findings would help urban planners to optimize the policies on allowing empty cruising for AVs.

6 CONCLUSION AND FUTURE WORKS

The findings of this research reveal that contrary to common perception, empty cruising strategy does not instantly increase the VKT (Research Question 2). In fact, at short duration (Iteration 2), this strategy can exacerbate the traffic congestion rather than increasing VKT. Although empty cruising strategy is expected to increase the network VKT, and it actually does in long term, the result of the experiment shows that allowing a short duration of empty cruising (under 10 minutes) actually reduces the VKT due to the significant reduction of parking search frequency (Research

Question 1) and parking search distance (Research Question 3) KPIs. In fact, rather than increasing the VKT, the empty cruising increases the parking search duration (Research Question 3) due to network congestion. As the empty cruising duration exceeds the 10 minutes threshold, the average parking search duration starts to reduce however this time the total VKT increase exponentially.

This observation shows that at early stages of empty cruising there is a trade-off between parking search duration and other KPIs (VKT, parking search frequency and distance) and as the empty cruising duration increase this trade-off transform to trade-off between VKT and other parking search KPIs (parking search frequency, duration, and distance). This trend indicates that formulating policies on empty cruising strategy by urban planners will significantly depend on the existing traffic congestion and the network capacity to accommodate empty cruising PAVs as well as the total parking demands. Therefore, when determining the optimal duration limitation on empty cruising strategy, the spatiotemporal characteristics of the traffic must be taken into consideration where variable-rate empty cruising should be allowed in different time of the day and also in different geographical locations.

The presented research in this paper can be further improved by some future research directions. One of these directions is to perform a cost-benefit analysis on empty cruising by allocating a cost element to the parking search frequency, duration, distance, and VKT KPIs. Such research helps to precisely determine the positive and negative impacts of empty cruising on parking dynamics, and to identify the optimal duration to create an equilibrium between the cost and benefit attributes. In addition, fuel consumption and CO₂ emission KPIs can also be analysed through the observed empty cruising impact on VKT which can help to better understand the environmental impacts of parking dynamics in PAVs' era. Moreover, since analyzing the parking dynamics depends on various parameters in different contexts, such as the number of trips, parking types, traffic congestion levels, and network topology, therefore a sensitivity analysis can be applied in future research to address the uncertainties of such a complex system. Another potential research is the analysis of outbound and inbound empty cruising impact on parking search dynamics and VKT KPIs. This can lead to clear understanding of empty cruising direction significance, and would enable to allow longer empty cruising duration limits without compromising on the parking search frequency, duration, and distance. Another potential research can be the investigation of the impact of allocating dedicated parking areas to PAVECs to drop and pick up their passengers to eliminate their parking search competition with HDVs in a mixed environment. These research directions for future work would enhance our comprehension of the spatiotemporal characteristics of empty cruising and aid to formulate an optimal policy framework in preparedness for transition into an AVs' era.

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