Self-Automated Parking Lots for Autonomous Vehicles based on Vehicular Ad Hoc Networking

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Abstract—Parking is a major problem of car transportation, with important implications in traffic congestion and urban landscape. Reducing the space needed to park cars has led to the development of fully automated and mechanical parking systems. These systems are, however, limitedly deployed because of their construction and maintenance costs. Leveraging on semi and fully-autonomous vehicular technology, as well as on the electric propulsion paradigm and in vehicular ad hoc networking, we propose a new parking concept where the mobility of parked vehicles is managed by a parking lot controller to create space for cars entering or exiting the parking lot, in a collaborative manner. We show that the space needed to park such vehicles can be reduced to half the space needed with conventional parking lot designs. We also show that the total travelled distance of vehicles in this new parking lot paradigm can be 30% less than in conventional parking lots. Our proposal can have important consequences in parking costs and in urban landscape.

I. INTRODUCTION

Autonomously-driven cars are only a few years away from becoming a common feature on our roads [1], [2]. These self-driven vehicles hold the potential to significantly change urban transportation. One of the most important changes will not happen during the trip from origin to destination, but rather when these vehicles arrive at their destinations. An autonomous vehicle will leave its passengers at their destination and will then park by itself, waiting to be called to pick them up later on. This behaviour will have important implications on door-to-door trip time, traffic congestion and parking costs.

As pointed out by Donald Shoup [3]: "A surprising amount of traffic isn’t caused by people who are on their way somewhere. Rather it is caused by people who have already arrived". Shoup refers to these phenomena as cruising for parking and shows that, despite the short cruising distances per car, this results in significant traffic congestion, wasted fuel and high CO₂ emissions [4].

With autonomous vehicles, the door-to-door trip time of a passenger will not be aggravated by the cruise time needed to find a parking space, nor with the walking time needed to go from the parking space to the final destination. Furthermore, after leaving their passengers at their destinations, these autonomous vehicles can rapidly proceed to a parking lot that does not need to be at a reasonable walking distance, as happens with non-autonomous vehicles. Nevertheless, the parking of these autonomous vehicles will still face the same problems of non-autonomous vehicles, since parking space is scarce and expensive.

If we consider the average 150 square feet of a parking space, and we assume there are 250 million vehicles in the USA, then a parking lot to contain all these vehicles would measure 1,350 square miles, roughly 0.04% of the country’s area. This does not seem much, but the problem is the concentration of vehicles in urban areas. As urban planners know, parking space is commonly allocated at a ratio of 1 space per 200 square feet of land use for a variety of businesses [5]. If we add an extra 30-50% of space for the access ways in typical parking lots, then we actually have ratios higher than 1:1 between the space allocated for parking and the space allocated for businesses such as supermarkets, shopping centres, office buildings, or restaurants. For example, in midtown Atlanta, in Georgia, USA, the percentage of land space that is 100% dedicated to parking reaches 21% [6]. This is one of the densest and most pedestrian-friendly area in the entire state of Georgia, USA. Parking is often the single biggest land use in many cities.

In parallel with the paradigm of autonomous vehicles, electric propulsion is also starting to be applied to automobiles. The electric motors used in Electric Vehicles (EV) often achieve 90% energy conversion efficiency over the full range of power output and can be precisely controlled. This makes low-speed parking manoeuvres especially efficient with EV. Another technological innovation being proposed to automobiles is wireless ad hoc vehicular communication, in the form of vehicle-to-vehicle (V2V) or vehicle-to-infrastructure (V2I) communication. The idea we present in this paper is based on the combination of autonomous
vehicles, electric propulsion and wireless vehicular communication to design a new paradigm of self-automated parking lot, which maximises the number of cars that can be fitted in the parking lot space, relying solely on in-vehicle systems.

The idea is relatively simple. An autonomously-driven EV equipped with vehicular communications (e.g. ITS G5, 802.11p standard [7]) consults online for an available parking space in nearby self-automated parking lots. It reserves its parking space and proceeds to that location. Upon entering the parking lot, this vehicle uses V2I communication to exchange information with a computer managing the parking lot. The vehicle can give an estimate of its exit time, based on the self-learned routine of its passenger, or on an indication entered by this same passenger. The parking lot computer informs the vehicle of its parking space number, indicating the exact route to reach this parking space. As vehicles are parked in a manner that maximises space usage (no access ways), this path can require that other vehicles already parked in the parking lot are also moved. The parking lot computer also issues the wireless messages to move these vehicles, which are moved in platoon whenever possible, to minimise the parking time. The exit process is identical. Minimal buffer areas are designed in the parking lot to allow the entry/exit of any vehicle under all possible configurations. The managing computer is responsible for the design of parking strategies that minimise the miles travelled by parked vehicles when performing these manoeuvres.

The remainder of this paper is organised as follows. In the next section we provide some background on parking lot technology. Following, we describe our system design issues. In the subsequent section we present the evaluation framework to compare our proposal with a conventional parking lot, leveraging on a dataset with entry and exit times of a real parking lot in the city of Porto, Portugal. We then evaluate a simple parking strategy for our self-automated parking lot proposal, based on this dataset, and compare the key metric of travelled distance in the parking lots, to show the feasibility of our proposal. We end with some conclusions.

II. PARKING TECHNOLOGY

Traffic congestion has for some decades been one of the major transportation problems due to its many and related causes. In dense urban areas, the search for an empty parking place can create considerable congestion, which results in economical losses and serious environmental impact. Searching for parking often occurs due to the imbalance between on-road and off-road parking prices, and the oversupply of free parking. A survey found that parking is free for 99% of all automobile trips in the United States [4]. In a historic study [3], Shoup reported that the average share of traffic cruising for parking amounts to 30% and the average search time is 8.1 minutes. In the same report, the author found that in a small business district in Los Angeles, cruising for parking leads to an additional 950,000 miles travelled, wastes 47,000 gallons of gasoline and produces 730 tons of $CO_2$ emissions. A comparable study [8] conducted in a district in Munich, Germany, shows a similar trend, i.e. wastes of 3.5 million euros on fuel and 150,000 hours, and 20 million euros in economical loss. Projected on larger cities in Germany, comprising multiple districts of similar sizes, a total economical damage of 2 to 5 billion Euros per year is estimated [8]. In [9], Ommeren et al. conclude that cruising time increases with travel duration as well as with parking duration, but falls with income.

A. Parking lot design

Parking also poses challenges to urban planners and architects. Considering that citizens often only use their cars to commute to and from work, the space occupied by these vehicles in urban areas is inefficiently used (e.g. currently the average car is parked 95 % of the time). Additionally, urban development has to consider local regulations that mandate parking space requirements depending on the construction capacity, which increases costs and limits buyers choices as demand surpasses parking space supply. A study in 2002 has estimated that parking requirements impose a public subsidy for off-street parking in the US between $127 billion and $374 billion [4].

In recent years, there has been an increasing interest in the design of parking structures. Parking lots consist of four main zones, namely circulation areas for vehicles and pedestrians, parking spaces, access to the parking infrastructure and ramps in multi-floor structures. Parking structure design compromises the selection of a number of parameters, such as shape (usually rectangular), space dimensions, parking angle, traffic lanes (e.g. one or two-way), access type or ramping options, depending on site constraints, regulations, function (e.g. commercial or residential), budget and efficiency reasons. Due to a number of reasons (e.g. existence of pedestrian circulation areas) parking lots for human-driven vehicles are inefficient and costly (e.g. smaller soil occupancy ratio), which is critical in densely populated areas.

B. Parking Systems

Extensive research has been carried out in the area of parking systems enabled by ITS. This research field is commonly classified into two main categories, namely parking assistance and automatic parking. Parking assistance systems, which are enabled by sensing, information and communication technology, support drivers by finding available on-street and/or off-street parking places. In these systems, acquired parking information (supply or demand) is disseminated to drivers, or its support systems, for decision making, i.e. parking space/route selection and eventually parking reservation and price negotiation. Examples of assistance systems are parking information system [10], [11] (e.g. guidance, space reservation), parking space detection (e.g. using GPS [12], cameras or sensors [13]), or parking space selection (e.g. based on driver preferences [14]).

Special attention has also been dedicated to the broad area of automatic parking. An early mechanical parking system [15] used four jacks to lift the car from the ground and wheels in the jacks assisted on the lateral movement towards
the final parking position. One of the major examples of this category is self-parking, where vehicles automatically calculate and perform parking maneuvers using sensor information (e.g., cameras, radar) and by controlling vehicle actuators (e.g., steering). An improvement to this system is Valet Parking [16], [17] where besides self-parking, the vehicle autonomously drives until it finds an available parking place. It should be noted that the two previous systems can be used for on-road and off-road parking (e.g., parking lots).

To reduce the space necessary to park vehicles, automated robotic parking has been deployed in areas where available space is especially scarce and expensive. These parking lots use electric elevators, rolling and rotating platforms to park vehicles in multi-floor structures, maximizing the occupancy of space. The parking maneuvers are done automatically by the electric platforms, without any intervention from drivers or operators. Automated robotic solutions are readily available in the market by several manufacturers, such as Boomerang Systems 1 or Parkmatic 2. However, due to their complexity, these systems require high capital investments and can have considerable operational costs (e.g., maintenance or energy costs), which can result in high costs for the end user. For instance, in many urban areas, the first hour of parking in such complex parking lots can reach $20. Another drawback of this solution is the absence of the Valet Parking feature since drivers need to bring vehicles into the closest parking place, which may not be the most appropriate (e.g., in terms of costs). Furthermore, the fixed size and small number of moving platforms limits the optimally of parking space allocation.

III. System Design

Our system design issues are described in this section. We address our assumptions regarding the self-driving capabilities of vehicles, the architecture and infrastructure of the parking lot, and a simple communication protocol which allows the parking lot controller to manage the mobility of the parked vehicles.

A. Parking Lot Architecture

The geometric design of the parking lot is an important issue in our proposal. As described in the previous section, in conventional parking lots there are a number of considerations that have to be taken into account when designing them. For instance, width of parking spaces and access ways, one-way or two-way use of the access ways, entry angle in the parking bays (90°, 60°, 45°), pedestrian paths, visibility to find an available parking space, etc.

In our self-automated parking lot, many of these considerations do not apply. Manoeuvring is done autonomously by the car, pedestrian access is not allowed, and the assigned parking space is determined by the parking lot controller. The main design issue is defining a geometric layout that maximises parking space, leveraging on minimal buffer areas to make the necessary manoeuvres that allow the exit from any parking space under all occupancy configurations. This geometric design is ultimately determined by the shape of the space of the parking lot. The parking lot architecture also defines the trajectories and associated manoeuvres to enter and exit each parking space.

The parking lot has a V2I communication device which allows the communication between the vehicles and the parking lot controller. In theory, this infrastructure equipment could be replaced by a vehicle in the parking lot, which could assume the function of parking lot controller while parked there, handing over this function to another car upon exit, similarly to the envisioned functioning of a V2V Virtual Traffic Light protocol [18]. Note, however, that the existence of the actual infrastructure, which could be complemented with a video-camera offering an aerial perspective of the parking lot to improve the controller perception of the location and orientation of vehicles, could simplify the protocol and improve reliability.

Reducing and simplifying such trajectories and manoeuvres is also an important design issue, as they affect the reliability of the system and allow faster storage and retrieval of cars. Note also that the parking lot architecture can take advantage of the fact that the passenger is not picking up the car at the parking lot, but it is rather the car that will pickup the passenger. This allows having different exits at the parking lot, which are selected based on the current location of the car. To optimise and simplify manoeuvres, these self-automated parking lots will require specific minimum turning radius values for vehicles. Only vehicles that meet the turning radius specified by each parking lot will be allowed to enter it.

The geometric layout of the parking lot and its buffer areas can assume very different configurations for the self-automated functioning. In particular, even parking areas which are not seen today as formal parking lots, such as double curb parking, could be managed by a similar parking lot controller.

As a proof-of-concept example, we provide the parking lot design illustrated in Fig. 1. This parking lot has a total of 10 × 10 parking spaces, and two buffer areas, one to the left of the parking spaces, and one to the right, measuring 6m × 20m. The size of the buffer area is determined by a minimum turning radius which was assumed to be 5m in this example, a typical value for midsize cars. As this parking lot is designed for autonomous vehicles, which enter it after leaving their passengers, it is not necessary to leave the inter-vehicle space that allows the doors to be opened. Thus, the width of the parking spaces can be significantly reduced (≈ −20%). In this example, we use 2m × 5m for each parking space.

This space-saving layout requires a specific strategy to guide the insertion and removal of vehicles. Ultimately, a layout is only feasible as long as the required movement by the vehicles does not have a significant cost. Next, we demonstrate a simple algorithm that exploits the exemplified layout. Later, in Section IV we evaluate its performance.

1 http://boomerangsyst.com/
2 http://www.parkmatic.com/
Fig. 1: An example layout for a self-automated parking lot. Buffer areas are used to allow the transfer of a vehicle from one line to another line, 5 positions above or below, as illustrated by the dashed trajectory lines.

B. Entry/Exit Algorithm

Consider Fig. 1. In this self-automated parking lot design, in order to simplify and standardise the manoeuvres, we use the buffer areas simply to allow the transfer of a vehicle from a given row to a new row which is 5 positions up or above (as dictated by the minimum turning radius of 5m), as illustrated by the semi-circle trajectories. This transfer of a vehicle from one row \( r \) to another \( r' \) will eventually require that other vehicles are moved and re-inserted in \( r \), in a carrousel fashion. This usage of the buffer areas is not particularly efficient from the point of view of space usage or mobility minimisation, but enables us to define a simple manoeuvring strategy of the parking lot that allows the exit of any vehicle. In this architecture we allow vehicles to enter/exit the parking lot through the left or right of the parking area.

A simple algorithm can then be defined as follows:

- **On Vehicle Entry**: the vehicle is directed to the topmost row \( r \), such that the eventual movement by vehicles already in \( r \) and \( r' \), to allow the entry of the vehicle, is minimised. The vehicle is placed in the nearest empty space in \( r \).
- **On Vehicle Exit**: the exiting vehicle parked in row \( r \) is directed to exit from the front or back, such that the eventual movement by the vehicles in \( r \) and \( r' \), to create an open path, is minimised.

C. Self-Driving Capabilities

In the specific case of our self-automated parking lot proposal, the autonomous driving capabilities of vehicles involve much simpler tasks than in the case of driving on public roads. Firstly, because the environment is fully managed by the parking lot controller and the only mobility that exists in the parking lot is determined by this controller. It is thus a fully robotised environment, where there is no interaction between autonomous vehicles and human-driven vehicles. In terms of technology and complexity, our setup is much more similar to Automated Storage and Retrieval Systems (AS/RSs), which have widely been used in distribution and production environments since its deployment in the 1950s [19], than to generic autonomous driving in roads.

Given that the parking lot controller coordinates all mobility in the parking lot, it knows the current configuration of the parking lot at all times. Thus, all the computer-vision technology, which plays an important part in autonomous driving, is not necessary in this controlled environment. More than self-driving capabilities, the cars that use the self-automated parking lot need to have a system to enable their remote control (through DSRC radios) at slow speeds in this restricted environment. Drive-by-wire (DbW) technology, where electrical systems are used for performing vehicle functions traditionally achieved by mechanical actuators, enable this remote control to be easily implemented. Throttle-by-wire is in widespread use in modern cars and the first steering-by-wire production cars are also already available [20]. EV will be an enabling factor for DbW systems because of the availability of electric power for the new electric actuators.

The precise localisation of vehicles is an important issue. In addition to global positioning systems, such as GPS, and to the aerial camera images, inertial systems from each car are also used to convey to the parking lot controller precise information about the displacement of each vehicle. This information can even report per wheel rotations, capturing the precise trajectories in turning manoeuvres.

Note that these limited requirements on the self-driving capabilities of the involved cars, would allow extending applicability of the self-automated parking lot to non-autonomous or semi-autonomous vehicles, which are left at the entrance of the parking lots by their drivers. While fully-autonomous production cars are still non-existent, automatic parking systems are already available in a number of production cars, based on research to control parallel parking manoeuvres of nonholonomic vehicles [21].

D. Communication Protocol

The communication protocol for the self-automated parking lot establishes communication between two parties: the parking lot controller (PLC) and each vehicle.

A vehicle trying to enter the parking lot, first queries the PLC for its availability. The PLC has a complete view of the parking lot state, mapping a vehicle to a parking space, and responds affirmatively if it is not full. Upon entering the parking lot, the autonomous vehicle engages in PLC-mode. During the stay in the parking lot, the PLC is responsible for managing the mobility of the vehicle. To move a vehicle, the PLC sends movement instructions in the form of a sequence of commands, similar to the commands used in radio-controlled cars, that will lead to the desired parking space. For example, the carousel manoeuvre described in Section III-A corresponds to the following sequence: forward \( m_1 \), steer \( d_1 \), forward \( m_2 \), steer \( -d_1 \), forward \( m_1 \). The commands depend on the vehicle attributes. These must be sent to the PLC when the vehicle enters the parking lot, i.e., width, length, turning radius, etc.

The protocol involves periodic reports sent by the vehicle to the PLC about the execution of each command (typically with the same periodicity of VANET beacons [7]). These periodic reports allow the PLC to manage several vehicles in the parking lot at the same time. Note that in order for a vehicle to be inserted in a parking space, other vehicles may
need to be moved. Note also that concurrent parking can occur in different parking spaces in the parking lot. Based on the periodic reports, the PLC tries to move vehicles in a platoon fashion, whenever applicable, in order to minimise manoeuvring time.

A vehicle exit is triggered by a message sent to the PLC by the vehicle intending to exit (possibly after receiving a pickup request from its owner). The PLC then computes the movement sequence commands and sends these sequences to the involved vehicles.

Having an external controller managing the vehicles poses evident security issues. As explained in [22], vehicular network entities will be certified by Certification Authorities, e.g., governmental transportation authorities, involving the certification of the PLC communication device of each parking lot. Temper-proof devices may avoid or detect deviations from the correct behavior. In the ultimate case, certifications may be revoked and new vehicles will not enter the park. For the parked vehicles that will not be able to detect the certificate revocation, no high risks exist.

IV. EVALUATION FRAMEWORK

In this section we describe a conventional parking lot layout and the layout used for our proposal of a self-automated parking lot. Our goal is to compare equivalent parking lots in terms of the number of vehicles that they can hold, using two important metrics: area per car; and total traveled distance in parking and exiting manoeuvres. The actual evaluation of this last metric using a real entry/exit dataset is done in the next section.

A. Conventional Parking Lot

For a comparative evaluation we use a conventional parking lot design, illustrated in Fig. 2. The design of this parking lot is based on a standard layout that tries to maximise parking space and minimise access way space, similar to the one seen in the dataset video, which we will discuss further ahead. We use the common measures of $5m \times 2.5m$ for a parking space and a width of $6m$ for the access way. Typically, two rows are placed facing each other, forcing cars to exit the parking space through a backup manoeuvre. The access way is based on a one-way lane, reducing its width and forcing cars to completely traverse the parking lot, in a standard sequence that consists of entering the parking lot, traversing it to find a parking space, parking, backing up to leave the parking space, and traversing the parking lot to proceed to the exit. This design allows us to discard variations in travelled distance when finding a vacant parking space is not deterministic.

This parking lot holds 100 cars occupying $72m \times 32m = 2,304m^2$. This yields an area per car of $23.04m^2$.

In this type of parking lot all vehicles traverse the same distance. The components of this distance are marked in Fig. 2. $A$ represents the straight distances travelled in the access way, while $B$ represents the curves. $C$ denotes the entering and exiting manoeuvre in the parking space. Using a turning radius of $5m$, we obtain the following total traversing distance for a car: $A = 94.8m$, $B = 6 \times (2\pi \times 5m)/4$, $C = 2 \times (2\pi \times 5m)/4 + 2 \times 3m$. This yields a total of $\approx 164m$ traversed by each car. It is clear that the manoeuvring model to derive such distance is over-simplified, but it results in negligible differences in our problem.

B. Self-Automated Parking Lot

For the self-automated parking lot we use the layout described previously. To be as equivalent as possible to the parking lot in Fig. 2, we use the $N_c = 10$ columns and $N_r = 10$ rows, forming a $10 \times 10$ array, comprising parking spaces, illustrated in Fig. 1. Two buffer areas are also included, with a width of $6m$ each, as in the access way of the conventional parking lot. As this parking lot is designed for autonomous vehicles, which enter it after leaving their passengers, it is not necessary to leave the inter-vehicle space that allows the doors to be opened. Thus, the width of the parking spaces is reduced to $2m$. The length of each parking space is again of $5m$. The total area of this parking lot is therefore $62 \times 20m = 1,240m^2$, yielding an area per car of $12.40m^2$. This represents a reduction of nearly 50% when compared to the area per car of the conventional parking lot.

In this self-automated parking lot the traveled distance can vary substantially from car to car, contrary to what happened in the conventional parking lot. As the autonomous vehicle leaves the parking lot to collect passengers at their location, we allow it to leave the parking lot either through the left or right buffer areas. It can also exit through a backup manoeuvre. Instead of deriving a single total distance traveled by each car, as in the conventional parking lot, we can try to derive the average distance that is travelled by each vehicle under special configurations of the parking lot. Note that vehicles will not be stopped in a fixed parking space, as the managing algorithm will move them to create the access ways during entries and exits of other vehicles.

To have an idea of the magnitude of the travelling distance in this self-automated parking lot, we can compute the entry and park distance for a special case where the parking lot fills completely in a monotonous process (i.e. no exits are observed). Let $\beta = 6m$ be the length of the entry buffer, and $\gamma = 5m$ the length of a parking space. Assume vehicles enter through the left buffer area of the parking lot. The first $N_c$ vehicles fill the furthest column, travelling a total of $N_c(\beta + N_c \gamma) = 560m$. The next $N_c$ vehicles fill the previous
column, travelling a total of 10(β + 9γ) = 510m. Iteratively, the total distance in meters to fill the parking lot is thus:

\[
\sum_{i=1}^{10} 10(\beta + i\gamma)
\]

which gives 3,350m, or an average of 33.5m per vehicle. This value is exactly the same that would be obtained if vehicles would park at the first available column, moving forward as necessary to accommodate entering vehicles, as described in Section III-B.

With a completely filled parking lot, the average travelled distance for the exit of each vehicle depends on the algorithm that creates exit ways by using the buffer areas. One possible alternative is to use the buffer areas as described previously, allowing vehicles to execute semi-circle trajectories based on their turning radius. If we use a turning radius of 5m, as in the conventional parking lot, then these semi-circle trajectories join line 1 to line 6, line 2 to line 7, etc., as illustrated in Fig. 3. If the red vehicle shown in frame A of Fig. 3 wants to exit, then all vehicles in lines 1 and 6 have to rotate clockwise using the semi-circle trajectories where necessary, until the red vehicle has no vehicles blocking it, as illustrated in frame B of Fig. 3. Note that the rotation can be counter-clockwise, as would be the case if the vehicle that wants to exit is vehicle number 5 in frame A of Fig. 3. These semi-circular trajectories can cause vehicles to be in different directions in the same row, but this is completely irrelevant in terms of the functioning of the parking lot.

![Fig. 3: Completely full parking lot. In this architecture, vehicles use the buffer areas to implement carrousels between lines 1-6, 2-7, 3-8, 4-9 and 5-10. Rotation can be clockwise or counter-clockwise.](image)

This usage of the buffer areas is not particularly efficient in terms of minimisation of travelling distance, but allows a simultaneous, platoon-based, mobility of vehicles, thus improving the overall exit time. As the manoeuvres are simple and standard, it also allows the derivation of an analytic expression that represents the average travelled distance for exiting vehicles under the full parking lot configuration. We consider \( c_i \) to represent a vehicle that wants to exit from the \( i^{th} \) column (\( i-1 \) vehicles in front). It varies from 1 to \( \frac{N}{2} \) = 5, as we consider the symmetry on clockwise and anti-clockwise rotations. Thus the average travelling distance for exiting vehicles is:

\[
\sum_{c_i=1}^{\frac{N}{2}} 2\left(\sum_{j=1}^{c_i-1} j\gamma + \gamma\pi\right) + (N_c - c_i - 1)\gamma + c_i\gamma + \beta
\]

(2)

This gives approximately 143.85m. Adding the average entry and park distance of 33.5m, we obtain a total per vehicle of 177.35m, which is similar to the 164m in the conventional parking lot. Note that in the conventional parking lot the 164m distance is fixed under all occupancy configurations of the parking lot, including nearly empty configurations. In the self-automated parking lot, the distance travelled in nearly empty configurations will be much smaller. Note also that a good parking strategy can minimise the exits of middle column vehicles, with important implications on the overall travelled distance.

C. The Entry/Exit Dataset

To realistically evaluate the travelled distance in our proposal of a self-automated parking lot we have to resort to a dataset with the observed entries and exits of an existing parking lot. The type of parking lot in terms of its usage can significantly affect the performance of the algorithm managing the mobility of the cars. For instance, a shopping mall parking lot will have a higher rotation of vehicles, with shorter parking times per vehicle, when compared to a parking lot used by commuters during their working hours. An important parameter to the algorithm optimising the mobility of the cars in the parking lot is the expected exit time of each vehicle, given at entry time. This time can be inserted by the passenger or automatically predicted by the car, based on a self-learning process that captures the typical mobility pattern of its passenger [23].

Our dataset is constructed based on the video-recording of the activity of a parking lot during a continuous period of 24 hours. The parking lot in question is cost-free, which affects the parking pattern. It serves commute workers, as well as a nearby primary school, causing some shorter stops of parents who park their cars and walk their children to the school. This parking lot has a total of 104 parking spaces, which we reduced to 100 in order to match our 10 × 10 layout, by ignoring the entries and exits related with four specific parking spaces. This parking lot is continuously open. It only has one entry point and we thus only allow vehicles to enter our self-automated parking lot through the left side entrance. We start with an empty configuration of the parking lot, ending 24 hours later, with some vehicles still in the parking lot. Table I summarises the key facts in this dataset. A histogram with the distribution of entries and exits per 30 minutes intervals is provided in Fig. 4. The dataset is available as a Comma Separated Values (CSV) file through the following link: http://www.dcc.fc.up.pt/~michel/parking.csv.
TABLE I: Key facts in the entry/exit dataset

<table>
<thead>
<tr>
<th>Feature</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parking lot location</td>
<td>(41.162745, -8.596255)</td>
</tr>
<tr>
<td>Start time</td>
<td>Dec 11th, 2013, 00:00</td>
</tr>
<tr>
<td>Duration</td>
<td>24 hours</td>
</tr>
<tr>
<td>Parking spaces</td>
<td>100</td>
</tr>
<tr>
<td>Total entries</td>
<td>222</td>
</tr>
<tr>
<td>Total exits</td>
<td>209</td>
</tr>
<tr>
<td>Average parking duration</td>
<td>3h38m25s</td>
</tr>
<tr>
<td>Average occupancy (0-24h)</td>
<td>34.76%</td>
</tr>
<tr>
<td>Average occupancy (9-17h)</td>
<td>74.59%</td>
</tr>
</tbody>
</table>

Fig. 4: A histogram presenting the number of entries and exits of cars per hour. We also plot the total number of cars in the parking lot. 100% occupancy is achieved at 16h05.

V. RESULTS

We implement a simple strategy to park cars, ignoring the estimated exit time that would be given by each entering car. Our strategy is simply to place the car in the parking space that requires a minimal travel distance of the cars in the parking lot. No optimisation based on the estimated exit time is used. Our goal is to show that even with such non-optimised strategy the total travelled distance is significantly less than in a conventional parking lot. Clearly, an optimisation strategy that uses the estimated exit times to order the vehicles in monotonic sequences would be able to give better results. Such optimisation strategy is however out of the scope of this paper.

The key metric that we evaluate is the total travelled distance of each vehicle, from entry time to exit time. Another possible metric would be the manoeuvring time. However, in our carrousel architecture vehicles are moved in platoon and thus total time is not affected by the number of vehicles in the platoon, but only by the distance travelled by the leading vehicle.

To measure this distance and to have a visual perspective of the functioning of the system, we implemented the self-automated parking lot architecture and mobility model using the Vehicular Networks Simulator (VNS) framework [24]. VNS was extended to model the specific features of our problem, namely the platoon-based mobility of vehicles. A video of this simulation under the dataset input is available through the following link: https://www.youtube.com/watch?v=CU_NJ2nAOGfd. The animation steps are based on the discrete entry and exit events, rather than on the continuous time, to eliminate dead periods.

A. Total Travelled Distance

A plot with the total travelled distance during the 24 hours we analysed is presented in Fig. 5, with two series representing the conventional parking lot (dashed red line), and the self-automated parking lot (solid blue line).

As can be seen, the reduction observed in total travelled distance is very significant. In the self-automated parking lot, we obtained a total travelled distance of 23,957.64m, for the 222 vehicles entering the parking lot (note that 13 vehicles remain in the parking lot after we end the simulation at 23:59:59). Using the fixed value of 164m for the conventional parking lot with the same number of entering and exiting vehicles, we obtain a total of 34,261.24m travelled distance, which translates into a reduction of 30%. Note that this reduction is obtained with a non-optimised strategy for parking vehicles. The non-optimised strategy affects primarily the performance during the period where the parking lot is nearly full (from 14h00 to 17h00), as the exits of middle-parked vehicles generates significant mobility of other parked vehicles, as can be seen in Fig. 5.

In Table II we present values for maximum travelled distance by a vehicle, average travelled distance and standard deviation. Fig. 6 shows the cumulative distribution function of distance per vehicle, where the linear behaviour is clear. Even the maximum value of 404m travelled by a vehicle translates into less than $0.05 according to the average operating costs of a fuel-powered sedan in the USA [25]. Note that the vehicle that travelled 404m stayed in the parking lot for approximately 16h, resulting in an average...
Fig. 6: Cumulative distribution function of distance per vehicle.

TABLE II: Travelled distance statistics per vehicle

<table>
<thead>
<tr>
<th></th>
<th>Maximum travelled distance</th>
<th>Average travelled distance</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_m$</td>
<td>404 m</td>
<td>112 m</td>
<td>87 m</td>
</tr>
</tbody>
</table>

The travel of 25$m$ per hour, which translates into an operating cost of less than $0.003 per hour.

VI. CONCLUSIONS

In this paper we have presented a new concept of a self-automated parking lot, where autonomous cars use vehicular ad hoc networking to collaboratively move in order to accommodate entering vehicles and to allow the exit of blocked vehicles. Using this collaborative paradigm, the space needed to park each car can be reduced to nearly half the space needed in a conventional parking lot. This novel paradigm for the design of parking lots can have a profound impact on urban landscape, where the current area allocated to car parking can sometimes surpass 20%. Our proposal is particularly effective with the emergent paradigm of EV, where very high energy conversion efficiency is obtained at the low speeds observed in parking lot mobility.

Our proposal, however, needed to show that the overall collaborative mobility generated in such a self-automated parking lot is not prohibitively high, compared to the mobility in conventional parking lots. Using a real dataset of entries and exits in a parking lot during a 24 hour period, we have shown that even using a simple and non-optimised strategy to park vehicles, we are able to obtain a total travelled distance that can be 30% lower than in a conventional parking lot. This non-intuitive result further strengthens the potential of our idea in re-designing the future of car parking.

Although out-of-the-scope of this paper, we have no doubt that the interesting optimisation problem that uses estimated exit times to determine the original placement for each car will be able to further improve the results reported here.