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Research Article

More Effective Use of Urban Space by Autonomous Double Parking

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The new capabilities of autonomous cars can be used to mitigate to a large extent safety concerns and nuisance traditionally associated with double parking. In this paper double parking for autonomous cars is proposed as a new approach to temporarily increase parking capacity in locations in clear need for extra provision when best alternatives cannot be found. The basic requirements, operation, and procedures of the proposed solution are outlined. A curbside parking has been simulated implementing the suggested double parking operation and important advantages have been identified for drivers, the environment, and the city. Double parking can increase over 50% the parking capacity of a given area. Autonomous car owners would (at least) double their probabilities of finding parking compared to traditional drivers, saving cruising time and emissions. However, significant work and technological advances are still needed in order to make this feasible in the near future.

1. Introduction

Most cities have areas where the provision of parking supply is unable to meet peak period demand. Consequently, many drivers are forced to seek an alternative parking location near their destination, creating environmental and economic impact in terms of increased traffic congestion, air pollution, and time delay for individuals who are searching [1–4]. A good case in point is an article published in 2010 by the Washington Post [5] stating that finding a vacant space in a 15-block business district in Los Angeles takes on average 3.3 minutes, involving 950.000 excess miles traveled and 47.000 gallons of gas wasted and 730 tons of carbon dioxide every day. In general terms, the magnitude of the problem is hard to ascertain as few cities have recorded evidences of the number of vehicles searching for parking. Shoup [6] reviewed 16 different studies in congested downtown areas around the world reporting that on average 30 percent of vehicles were searching for parking, with cruise time ranging from 3,5 to 14 minutes depending on the city which evidences that each municipality is a unique case. Effectively, the spatial organization of a city as defined by [7] (i.e., its spatial distribution of population and trips patterns) along with parking supply can be used as first approach to roughly estimate the level of parking search in specific areas of large cities. A good example of this kind of analysis can be found in [8] where the authors estimated the magnitude of the freight parking problem in New York City on the basis of curb space and trips attracted by commercial establishments per zip code. As the authors state "parking is even more of a challenge in old cities, in which narrow streets and land-use patterns that predate motorized traffic add an additional layer of complexity to the parking problem."

Different views on the parking problem and solutions arise from different actors with normally different interests. Local governments provide on-street parking supply, create regulations and policies, and enforce compliance. According to Mingardo et al. [9], parking policy trends have evolved from predict and provide (e.g., creating restricted parking spaces), to command and control (e.g., pricing parking), and,

(a) (b) (c)

Figure 1: Double parking in Seville (a), Nice (b), and Rome (c).

more recently, to managing demand (e.g., differentiated fees, promotion of remote park and go facilities, and massive use of IT to guide people and save cruising time; see initiatives listed in [4, 8]). Academia has also studied the problem of parking search and parking economics, contributing with analytical or simulation models [1–3, 10–13] and optimizing parking efficiency in scenarios such as curbside [10, 14], campus [15], freight traffic [13], or off-street parking [1, 16]. Private initiatives offer websites and smartphone apps to find parking in advance (e.g., Parkopedia [17], CarPark4you [18]) thus reducing the need for parking search. However, regardless of the measures taken, most drivers in congested large cities would agree that more parking supply is needed in destinations where, simply put, there are not enough parking space. A survey conducted among 374 drivers of commercial vehicles in Midtown Manhattan [8] revealed another undesirable consequence of this situation: illegal parking (e.g., expired/unpaid parking meter, noncompliance with the requirements of parking signs, or double parking). Unlawfully parked vehicles are estimated to cost 20 Million (Euro) every year to Barcelona or 2,5 Million (Euro) to New York according to Morillo and Campos [19].

Double parking is present in some metropolitan areas around the world. Figure 1 shows pictures of on-street double parking on the authors Campus in Seville (a), in a peripheral area in Nice (b), or in a commercial street in Rome (c). Double parking usually exhibits temporal and spatial patterns, happening spontaneously in destinations that attract a large number of people but which have a shortage of parking for peak demand (e.g., school drop-off/pick-up times, concert hall, load/unload, and market). Parking returns to normal state after the event or activity is over. According to the authors experience, in order to avoid major troubles, double parking should operate under the following rules: (a) the road use and traffic flow should be preserved (notice in Figure 1 that streets are usually wide and one-way; thus the remaining lanes are just narrowed) and (b) double parked cars should still let vehicles exit. The latter implies that a double parked car should be pushed away by those that want to exit, which can only be carried out with manual transmission cars left in neutral gear without handbrake and in leveled streets. Undoubtedly, the circumstances in Europe are more prone for double parking than in the USA in regard to either the adoption of manual transmission cars or the metropolitan spatial organization. However, according to the aforementioned survey [8] 10% of drivers of commercial vehicles in central Manhattan declared they double park for a short time period (load/unload) during peak hours presumably without leaving their vehicles completely unattended.

Double parking creates a negative impact in terms of shrinking the remaining road space available for other users, which in turn could slow traffic depending on the street speed limit. If unattended, double parking could also create occasional hazards as a result of maneuvering or cars pushed away from the parking area, unintentional hard collisions, or vehicle damage. Last but not least, it increases the exit time for drivers who find their car blocked, not to mention the physical effort required to push by hand those cars that prevent the exit. The previous reasons justify that double parking is illegal and generally perceived as something negative. However, it still happens every day in the streets of some cities, especially where officers overlook it as long as safety and traffic are not seriously compromised. In the authors' opinion, two possible reasons can be argued in support for permissiveness: (a) to preserve local economy and (b) simply in recognition that some destinations are clearly underprovisioned and drivers lack of reasonable alternatives.

But on the other hand, double parking can temporarily increase the supply in locations where the city cannot offer better solutions during peak hours. This paper proposes *autonomous double parking*, which basically consists of a self-organized double row made by autonomous vehicles which implement a series of capabilities suggested in this work. Our hypothesis is that, with the new capabilities offered by autonomous cars, most of the inconveniences associated with this practice (e.g., safety concerns, nuisance) can be mitigated to a large extent. As such, autonomous double parking could be postulated as a disruptive approach to temporarily increase parking supply in specific destinations where it was duly justified and traffic and safety were not severely compromised, thus reducing the occurrence of parking search. Although increasing parking supply can be controversial in the light of current trends in parking policy, it should be noted that we suggest the use of this practice only after a case-based thoughtful cost/benefit analysis.

To the best of our knowledge, the use of autonomous cars has been suggested to alleviate parking problems by driving away from the city center to large capacity multistory parking garages [15, 20] but not to create a self-organized double row (which is a more realistic short term goal). This paper takes a first step in suggesting a solution. Nonetheless, the aim is to add value in providing a conceptual foundation for

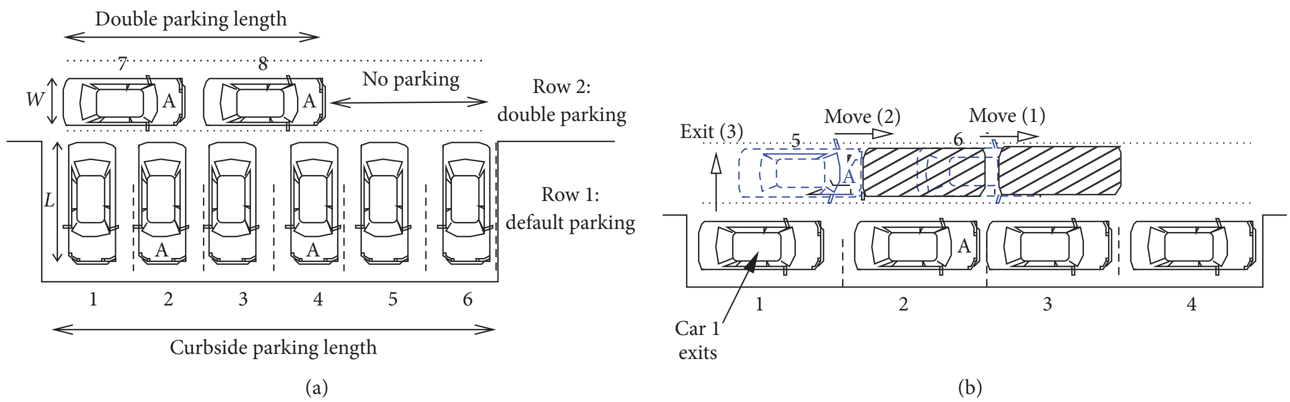


Figure 2: Example of double parking basic operation.

subsequent thorough refinement and development and to illustrate the potential benefits and limitations of this practice.

More specifically, the objective of this paper is twofold:

(i) To layout the operation, requirements, and applicability of autonomous double parking

(ii) To provide a preliminary analysis of performance which quantifies its potential benefits.

2. Autonomous Double Parking: Basic Operation and Procedures

Figure 2(a) illustrates a row of six vehicles (row 1) parked in a 90-degree angle to the curb (i.e., perpendicular parking). A second row (row 2), marked with dotted lines, indicates the space for parallel double parking. Here, the assumption is that row 2 can only be used by autonomous vehicles that implement such capability (marked with "A") whereas row 1 can be used by any type of car. Note that usable length of row 2 should be shorter than row 1 by at least $L+W$ (i.e., the largest length and width among the cars) in the studied scenario to let cars exit/enter row 1.

The basic operation is driven by the following two events:

(i) *Arrival*. Vehicles should park in row 1 if possible. If row 1 is complete, row 2 could be used by autonomous cars. If necessary, cars in row 2 will move to let arriving vehicles park in either row 1 or row 2.

(ii) *Departure*. Parked vehicles can leave anytime. If necessary, cars in row 2 will move to open a gap wide enough to let blocked cars exit from row 1. This is illustrated in the all-parallel parking example in Figure 2(b) where car 1 departure forces cars 6 and 5, respectively, to move forward before the exit.

The previous description is based upon the assumption that autonomous vehicles have the capability to coordinate themselves to create a gap of specific dimensions whenever and wherever is needed. This entails a number of requirements such as: (i) vehicles need to know the parking dimensions and their relative position; (ii) vehicles should be able to sense the distance between themselves and their neighbors in row 2; (iii) a vehicle-to-vehicle (V2V) distributed application has to be executed to convey information and commands to move; and finally (iv) the parking space should be equipped with some technology to provide information about its boundaries to autonomous cars.

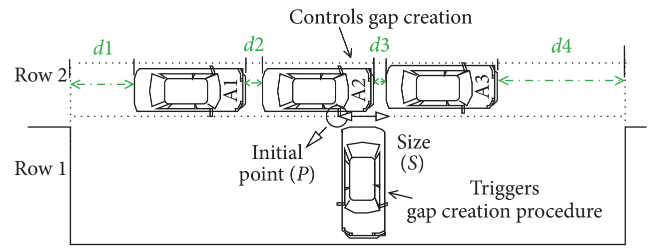


Figure 3: Main elements in gap creation.

A self-organized double row made by autonomous vehicles is advantageous with regard to the manual fashion described in Section 1 in terms of safety and comfort. Collisions or cars unattended out of the parking bounds after being pushed away should be drastically reduced. In addition, without manual pushing, physical effort is no longer required and exit time is reduced.

2.1. Procedure for Gap Creation

This procedure is the nuts and bolts of double parking. To illustrate it, an example of the exit of a blocked car is studied (see Figure 3). It is assumed that one car in row 2 receives the order to open a gap of size (S) at an initial spatial point (P). This car (A2 in Figure 3, also termed root for the remainder of this paper) takes control of the procedure execution until completion. It is also assumed that cars in row 2 cooperate until the operation is terminated, ignoring other calls in the meantime.

Then, car A2 (root) sequentially performs the following three broad steps:

(i) *Collect Information about Cars in Row 2*. It is assumed that each car i in row 2 knows its length (l_i) and width (w_i) and can sense its distance to neighbors or parking boundaries (d_i in Figure 3). Thus, cars in row 2 can

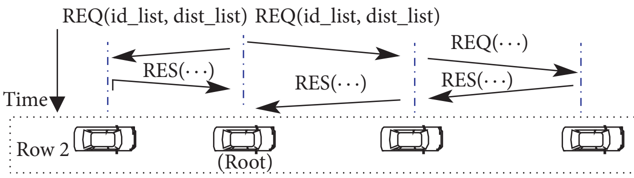


Figure 4: Communication flow for distance vector.

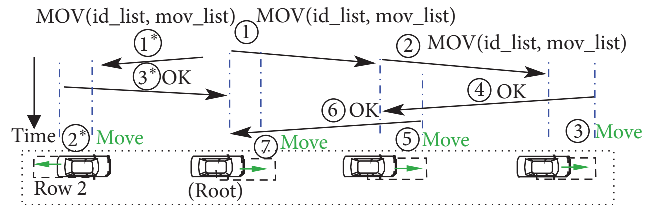


Figure 5: Communication flow for movement execution.

sense and send this information upon request as illustrated in Figure 4. The root car creates and sends a *Request* message to its neighbors. This message includes a list of car identifications (initially with only one item: the root), a list of intercar distances (initially with the gap from the root car to the next), and a flag indicating whether to go forward or backward. Each car receiving this message adds its own identification and intercar distance (edge cars add their distance to the parking bounds instead) and forwards the message until the accumulated gap amounts to the size S. Then, a new message *(Response)* is created. This message includes the previous information and follows the reverse path, indicating each car's confirmation to be engaged in this operation until completion.

(ii) *Determine Optimal Moves*. The root car executes an algorithm to find out the optimal moves to create a vacant space from P to $P + S$ minimizing the number of cars to move. The output of such algorithm provides the direction (forward or backward) and length of the movement to be performed by each car involved in the operation. Note that cars in row 1 can exit as long as $\sum d_i$ is greater than $\max(w_i) + \max(l_i)$. This constraint is assumed to be met throughout the paper. In the next subsection this algorithm will be elaborated.

(iii) *Order and Verify Movements*. Each car involved in creating the gap receives a request to move according to the algorithm output, starting with the outliers. Figure 5 illustrates the sequence of steps. First, the root car sends the movement vector to its neighbors which, in turn, resend this message. When the message reaches the last car on each side, the movement is executed and an acknowledgement message is sent back to the previous car which in turn performs the same operation. This is repeated until acknowledgments from both sides (the backward side is marked with $*$ in the figure) reach the root car, which is the last one to move. Note that some kind of visual or aural warning should be signaled by autonomous cars before and during their moves in order to warn other users such as pedestrians and pets.

Observe that the time to complete the procedure depends mainly on the number of cars involved in each operation (each car has to move a short distance, usually a fraction of S) which in turn depends on the actual state of the second row and the gap size and position. More specifically, because backward and forward sides can act simultaneously, the time to exit will depend on how many cars are moved on the *slower* side. The completion time will be addressed in the simulations results presented in Section 4.2.

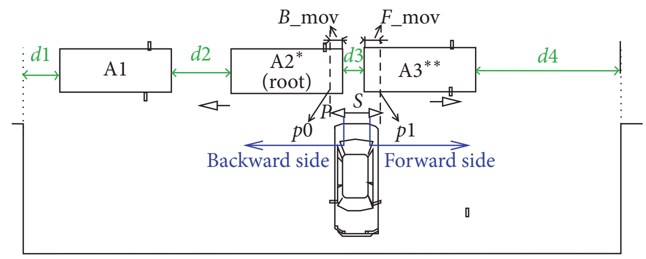


Figure 6: Illustration of key elements in the algorithm.

2.2. Design of the Gap Creation Algorithm. To elaborate the algorithm that determines the moves, the scenario in Figure 6 will be used. As default, it is assumed that two cars (A2 and A3 in Figure 6) are always next to point P (i.e., points $p0$ and $p1$ are in between their boundaries). The case where only one car is involved is simpler and can be viewed as a reduction of this example.

The algorithm steps are as follows:

(1) Find out the two cars whose boundaries lie within $p0$ and $p1$ (marked with $*$ and $**$, resp., in Figure 6) and calculate the distance to move forward and backward, respectively, in order to create the gap (B_{mov} and F_{mov}). Initially, the car marked with $*$ should move backward B_{mov} and the car marked with $**$ should move forward F_{mov}.

(2) Check B_{mov} and F_{mov} feasibility. The addition of all intercar distances on the backward side should be greater than B_{mov}. Similarly, adding all intercar distances on the forward side should let moving F_{mov}. If one of these two constraints fails, then only one car will be marked and moved to the opposite side. For example, if $d4$ was 0, car A3** would not be able to move forward. Then, instead of car A2, car A3 would be marked with $*$ and would have to move backward. Consequently, F_{mov} would be 0, and B_{mov} would be recalculated. After this step, B_{mov} and F_{mov} are definite and feasible.

(3) Calculate movements on both sides. The minimum number of cars to let car A2* move a distance of B_{mov} is searched for. This is readily done by adding intercar distances on the backward side starting with $d2$ until

the result is greater than B_{mov}. The same applies to the forward side.

The output of this algorithm is a vector with the direction and distance that each car should move (where null means no movement). Observe that the case where cars are moved only in one direction can be viewed as a case where either B_{mov} or F_{mov} is 0.

2.3. Other Procedures and Communication Flows. It is believed that in practice the following procedures can also be necessary in addition to the one described in Section 2.1:

(i) *Root Selection.* A procedure is needed to determine which one is the root car in case there are various candidates. A number of parameters could be considered for this such as car id, proximity to P.

(ii) *Abort.* There should be a way for aborting an ongoing operation due to irresponsive cars. A broadcast message should ensure that all cars are aware that the operation in progress has been canceled. Alternatives should be found to allow drivers to exit (e.g., an irresponsive car could also be considered as parking boundary without aborting the procedure).

(iii) *Completion.* After receiving the respective confirmations, the root car should broadcast a message informing all cars in row 2 that the operation in progress has successfully finished. Cars are then released from actual engagement.

(iv) *Exit/Arrival Signaling.* Drivers should have the means to signal their arrival/departure. In the case of autonomous cars this could be done through a communication protocol providing information about the car, gap position and size (i.e., P and S), and the operation (e.g., leave). However, nonautonomous cars should have other means to request this (e.g., horn beeping, touching door handler or a smartphone app). In this latter case, the root car would have to sense and infer somehow (maybe with the cooperation of other cars) both P and S. Arrival requests could be denied as a result of insufficient space in row 2.

3. Scenarios of Application

In our view, locations eligible for autonomous double parking should meet two minimum requirements: (1) there is a clear need for extra provision that cannot be better fulfilled otherwise and (2) traffic and safety are not severely compromised because of double parking.

Regarding the first requirement, some patterns or common situations prone to excessive parking search have been identified. In [4] a survey was conducted among local officials from different UK cities. There was consensus in identifying high levels of parking search in the following situations: (i) larger market downtowns with many attractors pulling a large number of visitors for shopping and personal business purposes but unable to provide sufficient parking supply for peak demand and (ii) peripheral urban areas away from the core city center that have a lack in parking facilities. Another situation identified in [8] was (iii) the freight parking problem in large urban areas, especially in old towns. Finally, the authors believe that (iv) off-street parking lots can also be considered for autonomous double parking as both customers and land owner can benefit from extra parking provision. Table 1 summarizes these scenarios.

However, not all locations meet traffic and safety minimum requirements. Among candidate locations, a second step would be to analyze plausibility and political justification. Obviously, the first requirement is that row 1 surroundings are spacious enough to allow double parking without severely impacting traffic congestion or safety. Parking spaces or lane size can be compacted up to a point but should still adhere to minimum standards as set up by national or local authorities.

Among plausible destinations (i.e., those which meet both requirements), a political decision should be made regarding authorization. A case-based cost/benefit analysis should be performed including the trade-off between the disadvantages (e.g., reduced road space, increased nuisance) and advantages (e.g., local economy, reduced parking search). Implications in policy follow from this second analysis. For example, in scenario A or C, keeping safety and congestion under control can be more challenging than in scenario B or D; consequently, enforcing parking time restrictions can be more important.

Parking areas should also be equipped with some technology (e.g., beacons, visual signs, or kind of systems such as those proposed in [20]) to inform at least the parking boundaries. No more complexity is strictly required to be installed in the parking as we rely on a vehicle-to-vehicle (V2V) system. But observe that an alternative vehicle-to-infrastructure (V2I) system can also be developed with the root car being a device installed at the parking facility. Finally, informative signs should be exhibited in the parking space indicating usage and specific rules for autonomous double parking (e.g., car type allowed, time restrictions, and pricing) including warnings and penalties for those impairing this practice.

4. Quantifying Potential Benefits

Clearly, the main benefit of double parking is the increased parking capacity. Assuming the average size of a vehicle is W (width) $\times L$ (length) (which includes extra space for opening doors), a curbside parking of length L_{park} can host up to $\lfloor L_{park}/W \rfloor$ vehicles in parallel or $\lfloor L_{park}/L \rfloor$ in serial manner. Adding a second row would provide approximately (ignoring the floor operator) a parking capacity increment (PCI) of

$$\text{PCI} \simeq \frac{W}{L} \cdot \left(1 - \frac{W + L}{L_{park}}\right) \quad (1)$$

$$\text{PCI} \simeq \left(1 - \frac{2 \cdot L}{L_{park}}\right) \quad (2)$$

for parallel (1) and serial (2) parking (see Figures 2(a) and 2(b)), respectively. Thus, for very large values of L_{park} and assuming that W is about half of L (coarse grained), the

Table 1: Potential scenarios of application.

Scenario type	Typical location	Benefit	Temporal pattern
A, attractive	Downtown street with attractors (school, market, bars, etc.)	Business, visitors	During attractions
B, residential	Peripheral streets underprovisioned	Residents	E.g., during night
C, freight	Center, market	Business	Load/unload
D, off-street	Business parking lot	Business, customers	—

asymptotic capacity increment would be 50% for parallel parking and 100% in the case of serial parking.

However, this extra capacity might not be fully used as a result of various reasons such as insufficient autonomous cars or the own parking occupation dynamics. In this section, these factors are evaluated through a series of simulations. The operation described in Section 2.2 has been implemented in MATLAB®. Then, a curbside parking is simulated where arriving cars can or cannot be autonomous with probabilities P_{auto} and $1 - P_{auto}$, respectively. Like in most works [1, 14], we assume that the parking occupation can be modeled as a birth and death stochastic process, with cars arriving, parking (if possible), and leaving after a certain random time. Two scenarios that differ in the parameters of the distributions used are simulated so that both transient and steady-state dynamics can be analyzed. Other studies addressing in more detail curbside parking occupancy dynamics can be found (e.g., [1, 10]). Our aim is nonetheless to illustrate and quantify the costs and benefits of our proposal and not to provide an in-depth study of parking occupation, which is left for further study.

4.1. Simulation Scenarios. The first scenario consists of a curbside parking of length 200 m where perpendicular parking is done in row 1 and parallel parking is allowed in row 2 such as in Figure 2(a). The main parameters of the simulation are as follows:

(i) Cars arriving: 204

(ii) Cars arrival: Poisson process with mean rate 204 cars per hour

(iii) Parking duration: exponential distribution (mean time 45 min)

(iv) Car length (l): uniform distribution between 4,5 m and 6 m (includes space needed to exit)

(v) Car width (w): uniform distribution between 2,9 m and 3,1 m (includes space needed to open the doors).

From the previous data one can estimate the average capacity of rows 1 and 2 to be 66 and 36, respectively (so the overall parking capacity is 102). This scenario is focused on transient dynamics (fill-up and depletion of the parking), so a mean arrival rate of 204 cars (2 × capacity) in one hour with an average parking duration of 45 min should be sufficient to fill up the parking depending on the share of autonomous cars. The simulation ends when the last car exits from the parking.

The second scenario is similar to the first one in terms of parking and car sizes (i.e., the same parking capacity). However, the following parameters are different:

(i) Cars arriving: 765

(ii) Cars arrival: Poisson process with mean rate 306 cars per hour

(iii) Parking duration: exponential distribution (mean time 5 hours).

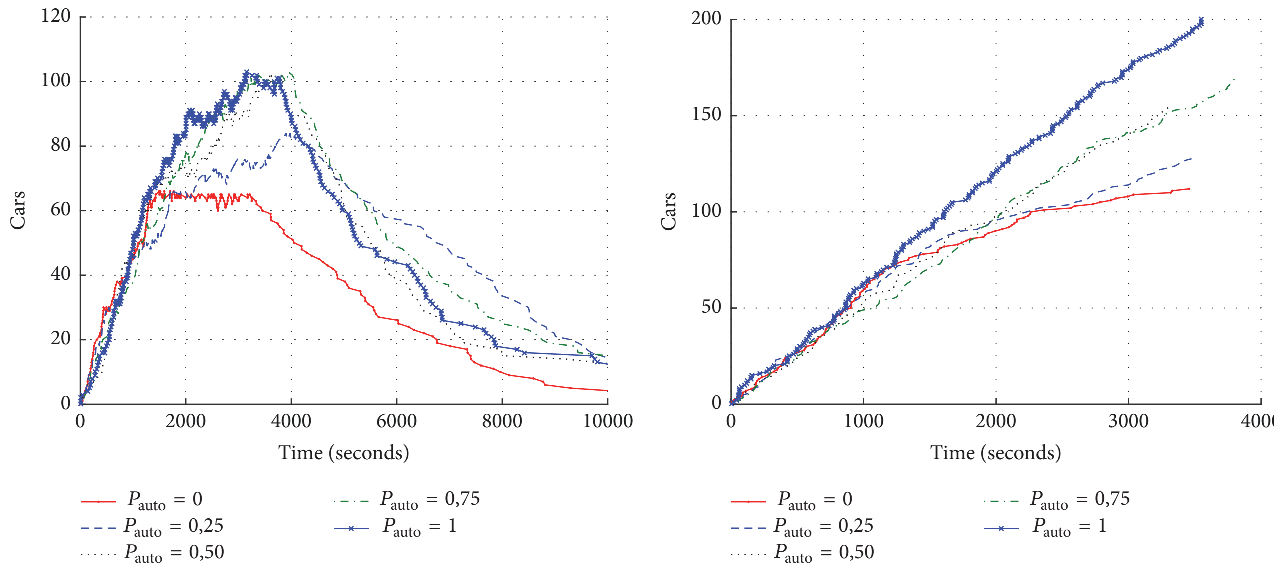
Most cars will arrive on average over the first 150 min at a rate three times the capacity, and parking duration is 5 hours on average. Consequently, it is expected that the parking exhibits full occupancy over an extended period of time. This will let us examine the steady-state situation when fewer vacancies are taken as a result of long term parking.

4.2. Results. Before introducing the main results it is worth examining the parking occupation dynamics through the study of one simulation of the first scenario with different values of P_{auto}. Figure 7(a) provides the evolution of the number of parked vehicles over the first 10^4 seconds of the simulation. Figure 7(b) provides its cumulative value. Fluctuations in the series of Figure 7(a) can be attributed to exits followed by arrivals. We can distinguish four different phases in the occupation dynamics. The first one corresponds to the occupation of row 1 at a rate proportional to the arrival rate (which is independent of P_{auto}). The next phase starts after row 1 is full. In this second phase row 2 is occupied at a rate approximately proportional to the arrival of autonomous cars (i.e., arrival rate $\times P_{auto}$). A third phase can be observed when the parking is full and fluctuations occur as a result of scarce vacancies amid new arrivals (this can be observed for $P_{auto} = 0$ or 1 in Figure 7(a)). The last phase starts when the occupancy monotonically decays as there are more cars exiting than arriving. It can also be observed in Figure 7(b) that the number of successful parking attempts tends to increase with P_{auto} which can be traced back to more arrivals to row 2.

Figure 7 represents just one simulation run and has illustrative purposes. Nonetheless, the results presented in the remainder of this section will average the output from 100 simulation runs, providing a level of statistical significance of $\alpha = 0{,}05$. The statistics collected in the simulations are as follows:

(a) *Parking Successful.* Percentage of successful parking attempts

(b) *Row 1 Use.* Number of cars parked in row 1



(a) Parking occupation

(b) Cumulative number of parked cars

Figure 7: Dynamics of the parking occupation in terms of (a) number of cars during the simulation and (b) its cumulative value.

(c) *Row 2 Use.* Number of cars parked in row 2

(d) *Operations.* Number of gap creation operations

(e) *Starts.* Times that a car in row 2 has moved on average as a result of gap creations

(f) *Distance.* Overall distance (in meters) moved on average by a car in row 2 as a result of gap creations

(g) *Autonomous.* Percentage of autonomous cars successfully parked

(h) *Nonautonomous.* Percentage of nonautonomous cars successfully parked.

Table 2 shows the results obtained for the first scenario: 204 cars arriving at a rate of 204 cars/hour to a parking with 102 spaces (66 in row 1).

Row (a) in Table 2 shows that the probability of a driver finding parking rises from ~62% to 91,5% when all cars can double park. However, rows (b) and (c) show that this improvement is experienced only by drivers of autonomous cars, who have over 99% probability of finding parking when $P_{auto} \leq 0,5$ (g). The average number of vehicles that used the second row ranges from 4,6 (12,7% of row 2 capacity) to 59,2 (164% of row 2 capacity) for $P_{auto} = 1$. Consequently, double parking has increased up to 46% the number of vehicles that used the facility in this simulation study.

Owners of autonomous cars have saved cruising time because of the right to exclusive use of row 2. However, a cost has to be paid in terms of autonomous moves due to gap creations and waiting time to exit. In this respect, row (d) shows that the number of gap creation operations increases with row 2 occupancy, ranging from 12,5 ($P_{auto} = 0,1$) to 87,3 ($P_{auto} = 1$) operations over a period of 45 min (average parking duration). However, these operations do not implicate all cars in row 2. Combining rows (c), (d), and (g) one can estimate that each operation implicates between 2,42 ($P_{auto} = 0,1$) and 7,66 ($P_{auto} = 1$) vehicles on average. Considering that cars can be moved either backward or forward and that this can be performed simultaneously, the waiting time to exit entails the movement of 2–4 cars on average. Regarding the economic cost, an average double parked car will end up starting between 6,6 and 15,6 times, driving a cumulative distance between 17,5 and 42,2 meters.

In the second scenario 765 cars arrive at an average rate of 306 cars/hour over an extended period (150 min on average). Now, the parking duration is 5 hours on average. This suggests that the occupation rate will be faster and also that once the parking is full, more cars will not find a space with respect to the first scenario. This is confirmed in Table 3, where row (a) shows that more than 80% of the arriving cars cannot find vacancies in the facility. Now the probability of a driver finding parking rises from 12,5% to 19,1% when all cars are allowed to double park.

Row 2 average usage ranged from 47,7 to 51,1 vehicles (142% of row 1 capacity). Autonomous double parking has increased up to 53,9% the number of vehicles that used the facility in the simulation. However, using the duration and arrival rate, we can go further in this reasoning. On average, after 2,5 hours, only half of the parking will have exited (as the average parking duration is 5 hours); then, dividing the number of cars that have used the parking (approximately 150) between the number of vacant spaces created from the beginning of the simulation (approximately 1,5 times its capacity, 153), it can be seen that the parking occupation consistently reaches the 98%. This result suggests that, effectively, the facility reaches full occupancy fast and remains saturated afterwards. Precisely, this fact also explains why, unlike the first scenario, the occupation in row 2 does not exhibit large variations with P_{auto}.

The number of gap operations remains approximately constant around 73. Since the average parking duration is 5

Table 2: Results, first scenario, 204 vehicles.

P_{auto}	0	0,1	0,2	0,3	0,4	0,5	0,75	1
(a) Parked	61,9%	64,6%	67,6%	72,3%	75,1%	77,8%	84,5%	91,5%
(b) Row 1 cars	126,2	127,1	127,5	129,6	127,7	127,2	127,3	127,5
(c) Row 2 cars	0,0	4,6	10,4	17,8	25,6	31,5	45,0	59,2
(d) Operations	0	12,5	24,2	40,2	54,1	63,4	80,3	87,3
(e) Starts	0,0	6,6	10,1	13,4	15,6	15,6	15,2	11,3
(f) Distance	0,0	17,5	24,9	30,8	35,5	35,7	42,2	33,1
(g) Autonomous	0,0%	99,6%	99,5%	99,4%	99,6%	99,1%	93,9%	91,5%
(h) Nonautonomous	61,8%	60,7%	59,9%	60,6%	58,5%	56,9%	55,7%	0,0

Table 3: Results, second scenario, 765 vehicles.

P_{auto}	0	0,1	0,2	0,3	0,4	0,5	0,75	1
(a) Parked	12,5%	18,6%	18,9%	19,0%	19,3%	19,1%	19,1%	19,1%
(b) Row 1 cars	94,9	94,0	93,6	94,9	95,6	94,7	94,5	94,8
(c) Row 2 cars	0,0	47,7	50,9	50,4	51,6	51,2	51,5	51,1
(d) Operations	0,0	69,7	73,2	73,5	74,8	72,8	73,8	73,2
(e) Starts	0,0	12,2	12,1	12,8	12,0	12,1	11,9	11,8
(f) Distance	0,0	34,6	38,8	44,7	41,9	44,9	44,7	46,6
(g) Autonomous	0,0	74,8%	45,7%	34,6%	29,3%	25,9%	21,4%	19,1%
(h) Nonautonomous	12,4%	12,3%	12,2%	12,3%	12,6%	12,2%	12,3%	0,0

hours, this is about one every four minutes. An operation involves about 8,2 vehicles on average, more than in the first scenario. This is traced back to the fact that row 2 is full for most of the simulation and, hence, space is more fragmented. Finally, an average double parked car ends up starting about 12 times as a result of gap creations, driving a cumulative distance between 34,6 and 46,6 meters. Again, differences with the first scenario can be attributable to the fact that cars are involved in more moves on average.

4.3. Discussion of Results. After analyzing the results from the two scenarios, the following points can be made:

(i) *Driver's Perspective.* Owners of autonomous cars will always find parking in the first two stages of the parking dynamics. In the two studied scenarios drivers of autonomous cars have at least twice more chances of finding parking than drivers of nonautonomous cars. In the first scenario, the probability of finding parking for a driver of an autonomous car is greater than 99%. Even with $P_{auto} = 0{,}1$ (which is more realistic in the short term), autonomous car drivers would have a considerable advantage in both scenarios. The cost of this advantage does not seem to be burdensome in terms of time to exit (i.e., waiting for 8 cars to move in the worst case) when compared with cruising somewhere else.

(ii) *Environment's Perspective.* Moving autonomous cars during gap creations can be seen as a cost. In our worst case scenario a car is moved 15,6 times on average (in 45 minutes) as a result of gap creations to perform very short movements, adding up to 46 meters. At any rate, failing to park implies cruising somewhere else which is likely a worse option in terms of emissions according to results shown in [10]. It is worth noticing that modern autonomous cars are expected to exhibit high standards of efficiency and emissions.

(iii) *City's Perspective.* In the studied scenarios, the addition of row 2 has increased the capacity of the parking facility about 50%, and its use has also increased over 45%. This extra capacity can be potentially extended to justified locations, encouraging a wider adoption of autonomous cars. This is aligned with modern approaches in parking policy as described by Mingardo et al. [9]: proactive management, improving the quality of life, and making massive use of IT to avoid unnecessary cruising.

5. Open Issues and Future Directions

This paper takes just a first step in suggesting a solution. Significant efforts have yet to be made by many actors to make double parking feasible. The following research directions or problems can be identified:

(i) *Application Protocol.* A standard vehicle-to-vehicle double parking protocol has yet to be developed and adopted by the industry. Current communication standards for Intelligent Transportation System (ITS) such as CALM [21] or WAVE [22] should provide support for this.

(ii) *Perception and Cognition.* More accurate (i.e., more than GPS) and reliable sensing of distance, self-localization, gap dimensions, obstacles (e.g., pedestrian position and velocity), and so forth has to be possible to implement the suggested solution. Artificial vision and multisensor fusing are promising approaches in this field [23]. However, as stated in [24], “today’s sensors are capable of collecting detailed data of a car’s surrounding environment, but machine cognition and situational awareness are still in their infancy.”

(iii) *Modeling and Simulation*. More complete simulations with finer models and calibrated with parameters extracted from real cases should be performed. Variations of the suggested operation could also be explored in order to improve the performance (e.g., simultaneous versus sequential movement, minimizing the distance instead of the number of cars).

(iv) *Problematic Situations*. Problems might occur when either autonomous cars do not cooperate or drivers of nonautonomous cars park in row 2. Potential problematic situations and its consequences should be carefully studied and remedies suggested to guarantee that cars parked in row 1 can always exit.

(v) *Regulations and Policy*. A case-based analysis should determine whether autonomous double parking is the best option for each location. A deeper study of the benefits and disadvantages of this practice (including sustainability) is needed in order to identify the constraints of the space of acceptable solutions. Existing restrictions (spatial, temporal) or parking pricing should be analyzed in the light of double parking. For instance, it might be helpful to apply a harder time restriction to double parked cars in order to achieve a higher turnover or make it free in order to foment its use.

6. Conclusions and Further Work

Autonomous double parking is a new idea which has the potential to benefit drivers, cities, and the environment under the right circumstances, which should be determined by a case-based cost/benefit analysis. Autonomous vehicles equipped with the suggested capabilities can save cruising time and emissions thanks to the increment of the parking capacity in locations in need for extra provision or by off-street parking owners. Indirectly, people are encouraged to buy more efficient cars, helping also in developing smart cities and benefiting the car industry. However, important technological advances and research are still needed to make autonomous double parking feasible down the road. Developing a widely adopted standard protocol and improving the sensing capabilities of present vehicles will be key in the success of this proposal.

We are presently working on creating simulations that use parameters calibrated with real cases on each scenario defined in Section 3 and more complete models (e.g., accounting for the traffic flow into and out of the parking area) which should provide richer results.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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