# Multi-Agent Navigation of a Multi-Storey Parking Garage via Game Theory

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***Abstract*—Intelligent autonomous vehicles navigating in a smart city environment need to find a parking spot, and often resort to multi-storey parking facilities. The task of efficiently using parking resources is at odds with the competitive nature of autonomous vehicles operating in a selfish way. In this paper, we model the problem through game theory and we evaluate the efficiency of a distributed decision mechanism. At the same time, we also gain insight on the complexity of identifying efficient solutions and hint that the overall problem is difficult to solve without compromising the inherent selfish objective of each individual vehicle. We also propose some distributed simulation scenarios to capture some aspects of the competition, thereby suggesting possible further analytical studies.**

## I. Introduction

Smart cities are expected to face many issues related to vehicular traffic and its efficient handling [1]. One pressing problem is represented by car parking in downtown areas where commuters converge. Notably, even in the case that the entire downtown area relies on public transportation and/or consists of pedestrian zones, the problem is just deferred to the management of multi-storey parking facilities in the close proximity of the city centre [2].

The number of public park spaces in Europe alone is around 300 millions. Multi-storey parking lots are estimated to be in the order of tens of thousands [3]. These numbers make the problem of an efficient management of such structures particularly relevant. At the same time, it is estimated that in many metropolitan areas of Europe, North America, or Japan, the average driver spends almost one day every year looking for a parking spot. For example, [4] and references therein report that the average time spent per year in a parking facility is 17 hours in the United States of America, with peaks of more than 100 hours, for example, in New York City. This immense amount of slow driving is done while the engine is running, which to leads not only inconvenience for the drivers but also lots of unnecessary $CO_2$ emissions. Thus, approaches to this problem would also insert in the context of finding energy-efficient and environmental-friendly solutions for smart cities [5].

However, the development of good searching strategies for a parking spot contrasts with the nature of the problem itself. While coordinated solutions could be conceived, impatient drivers are hard to organize and not cooperative, since they pursue selfish goals, i.e., they tend to compete for the limited resources available rather than collaborate. Additionally, drivers moving in a parking facility operate with limited information about decisions of other drivers and can reasonably assume them to be self-centered. In other words, this setting fulfils most criteria that are typical of game theory, which is a cross-disciplinary approach that is gaining momentum also in relationship to networks and smart city scenarios [6], [7].

Despite these properties of the problem at hand, and the increasing interest of the scientific community towards solutions for smart and interconnected vehicles, we found that the literature is surprisingly scarce of game theoretic investigations in this context. While there are indeed some papers on applications of game theory to the problem of parking cars [8]–[10], none of them considers the scenario of a multi-storey parking facility. Such an assumption further complicates the approach, since it is expanded from a single domain of competition to a multi-layer competition. Also, the general conclusion from the literature is simply that the problem is essentially hard because, due to the symmetric character of all the vehicles from a theoretical standpoint, there is no solution of the one-fits-all kind.

Based on this existing background, we take a different direction in that we explicitly model a scenario for a multi-storey parking facility. We start from a theoretic analysis of the possible strategies to be used in such a context, where, akin to the existing literature, we show that the problem has a clearly inefficient Nash equilibrium and also prohibitive computational complexity. However, based on the established game theoretical framework, we are able to analyze some intuitive scenarios, which we believe to be promising to generate future approaches to the problem. For complexity reasons, this analysis is carried out by means of simulations. Still, we are able to highlight some possible heuristic choices that can lead to more efficient descriptions of the problem for future developments.

The rest of this paper is organized as follows. Section II reviews related work about smart car parking and game theory, and discusses some original traits of the scenario at hand. In Section III, we present a model of the problem as a tragedy of commons, where we find that the best strategy for the players is a simple scan of the available levels. Section

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IV describes some possible variations of the scenario, where we account for further elements available to the players and/or we investigate possible characteristics of the drivers in a simulation context. Section V discusses some numerical results and finally Section VI concludes the paper.

## II. Related Work

The general idea that smart car parking is one of the prominent IoT-assisted application in future smart cities is quite commonly encountered in the literature [11], [12]. However, the main focus of the vast majority of the papers is the architectural implementation of the information exchange across individual heterogeneous devices as the enabler for smart solutions of car parking, allowing for notification exchange about the availability of a parking spot [4], the controlled access and recognition of vehicles [13], and notification and possibly fining of violations [14].

We take a different approach, where we give such a platform for granted and we challenge the essence of the problem as a strategic interaction of multiple intelligent agents. These can be the drivers themselves, or even automata controlling the vehicles, which is certainly a not so distant reality [15]. As a side note, automating the entire process through an AI-assisted parking procedure would have the additional benefit of relieving human drivers from navigating through a multi-storey parking facilities, which is investigated in the literature as being sometimes perceived as claustrophobic or unsafe [16], and where the pollution of exhaust emissions in a closed space causes a poor quality of the air [17].

Overall, our idea is to explore solutions from a mathematical standpoint, for the parking facility considered as a shared pool of a discrete resource (the parking spots), which results in a multi-person multi-agent optimization. The instrument of choice for this analysis is game theory [7], which is exactly designed to investigate such problems. Yet, despite transportation problems in smart cities being quite an ideal scenario for the applications of game theory [6], we found out that the investigations about the problem of parking cars in shared stationing areas are scant, and even more so when specific constraints about the structure of the resources are given, as is the case for a multi-storey parking lot.

One notable reference is [8], where the problem of assigning parking spots is addressed from a general perspective as a complete or incomplete information game. The main finding is that the problem is inherently difficult, with unbounded Price of Anarchy (PoA), and high computational complexity. For this reason, a heuristic gravitational approach is proposed. The authors of [9] expand from this result by considering the possible structures of a Nash equilibrium for $D$ competing drivers, and basically deduce an admission control procedure that limits the value of $D$ to a suitable level. This is achieved through some priority heuristic modeling accounting for individual traits of the drivers. In [10], the problem is modeled as a Stackelberg game with the additional intervention of a primary player representing an authority body, which is a standard way out from the unbounded PoA.

However, none of these contributions explicitly addresses the key aspect that we consider here, which is, the resource shared in a multi-storey parking is not a homogeneous good. Navigating through different levels can be time-consuming and stressful for the drivers and needs to be captured in the utility functions that are guiding the agents in their choice [18]. Naturally, this exacerbates the inherent inefficiency of the competition, already present when the shared resource is homogeneous. Individual characters of the agents can be certainly included to further differentiate among them and break symmetries, which is generally beneficial to prevent the PoA from exploding [19].

Finally, given that the inherent complexity of the problem is backed by theoretical findings, we also consider a practical approach through a multi-agent simulation. We believe that such a direct framing of the problem, which is also meaningful in the context of smart cities [20], can be convenient in setting possible ideas for future viable policies to implement in real devices.

## III. Model of the Competition as a Game

The game is described in its basic form by a set of independent non communicating agents who share an environment, which in our case consists of a multi-storey garage with some pre-defined numbers of levels and parking spots per floor. Agents enter the facility on the ground level (denoted as 1) at some point of the game determined by chance. In game theoretic jargon, this is said to be a decision made by a virtual player called *Nature*.

While positioned at level $\ell$, $1 \leq \ell \leq L$, the agent has the options to go up a level (except on level $L$), go down a level (except on the ground level) and search the level. If one player searches a level with a free spot, the player takes it. If two or more players search a level with fewer free spots than them at the same timestep, a collision resolution occurs, which corresponds to a random allocation of spots among them: in other words, if $n$ players simultaneously search for a spot in a level with just $k < n$ spots available, $k$ of them get the spots, and this is determined by chance (once again, another choice made by Nature).

A player that found a free place has no more decisions to make in the game and has a final immutable utility. The utility of each player is computed based on the amount of levels searched and levels changed. In the numerical evaluations, we consider a cost $C_M = 3$ for each move upwards or downwards of a level, and a cost $C_S = 7$ of searching for a free parking space on a given floor. This set of rules constitutes the simplest basis of the problem. We remark that the actual numerical choices of these costs do not impact significantly the final results, as long as they correspond to an increasing cost for more level transitions and/or unsuccessful searches. Since the utilities mostly have an ordinal meaning [7], there are actually many equivalent choices of increasing cost functions that would fit the same intuition. For a more detailed discussion about the heuristics and how to model the utility of a car parking result, the reader can also refer to [18] that offers a comprehensive review.

Albeit the formalization of the game is simple, its computational complexity grows quite rapidly even for a small parking garage and a couple of players. The decision tree of the extensive form of such a game quickly increases in width, reaching a space complexity of $O(N^3)$, where $N$ is the number of players, and becoming more spread out at every in-game timestep. The game is also not finite for some sets of choices, players can repeatedly go up and down or search through full levels indefinitely. To be able to compare strategies, we introduce reasonable restrictions, like not allowing to go down right after going up and forcefully stopping the game at a given timestep, punishing still active players. Still, even these artifices make the computational complexity prohibitive for an exact analysis: for example, a full game with 4 players, 4 levels, 2 parking spots per level and a time limit of 10 timesteps has 1363 final outcomes.

Another problem with the extensive form of the game, i.e., its representation through a decision tree, is that the vehicles do not really enter the parking garage simultaneously. Their order of entering determines whether they will find a spot. However, we take the game theoretic stance of modeling the players' strategies as decisions made *a priori* and not as behavioral choices. In other words, the strategy of a player is defined as a list of commands to follow, which would make much sense in the context of smart vehicles moving as controlled by automated programming [15]. In this context, the character of a player of being the first to enter, or last, or anything in between, could be framed as a Bayesian type [19], since it ultimately impacts the utility and determines whether a strategy is efficient. However, it also makes sense that this aspect of the gameplay, decided by Nature, is not disclosed to the individual players and remains a random element of the game. In actuality, by the time of choosing a strategy, each player has no knowledge whether it is entering first, last, or in between. Thus, an optimal strategy for a player should on average outperform other strategies if played repeatedly with different entering times.

In our scenario, we model this as an initial move of Nature, before any player decision. When players enter the garage, they do not know their time of entering (nor their position in the overall order, even). However, to respect the game theoretic conditions, they have uniform probability $1/N$ of occupying each order position, where $N$ is the number of players. Also, we assume that $N$ and the uniform distribution of this Nature's choice is common knowledge among the players.

This unknown time of entering makes the setup fully symmetrical to all players, and this is also common knowledge. All decisions can be seen as simultaneous, because players do not gain any new knowledge during the game. For each player, this means that, before entering the parking garage, a fixed sequence of moves is chosen for the game, for example 'UUSUSDDS' (Up, Up, Search, Up, Search, Down, Down, Search). A player follows this strategy until the game ends, either by finding a spot or because the game is forcibly terminated when a maximum number of rounds is reached. Given that this information is also fully available to perfectly rational players, it follows that a Nash Equilibrium of the game can be found by symmetrically playing the average-best strategy for all players.

So, we ran the game many times and analyzed the outcomes. In these runs, we considered all combinations of strategies and entering sequences. We also considered different values of $N$ and different garage parameters, such as the number of levels $L$ and search or moving costs. In spite of the results being purely enumerative, it is still possible to draw some general conclusions, since the outcomes are very consistent. Different garage sizes or costs of moving/searching do not impact the ranking of best performing strategies. As an example, Table I reports the top 10 best strategies and their utilities for a game with 4 levels, 2 spaces per level and 4 players. Once again, we remark that the utility values are reported just for the sake of completeness, but the most important aspect is the preference order, which would actually be the same for a wide array of numerical choices.

TABLE I: Best strategies and their utility values for a static symmetric competitive game

| strategy | utility value |
|---|---|
| SUSUSUS | -5.2 |
| SUSUUSDS | -5.6 |
| SUUSDSUUS | -6.0 |
| SUUSUSDDS | -6.4 |
| USDSUUSUS | -6.4 |
| USDSUUUSDS | -6.8 |
| USUSDDSUUUS | -6.8 |
| SUUUSDDSUS | -7.2 |
| SUUUSDSDS | -7.2 |
| USUSUSDDDS | -7.2 |

This confirms that the best strategy for a player is to search the ground level first, and if it is full, to continue with the upper levels in increasing order. This is a pretty intuitive behavior that people normally show in parking facilities, where they know nothing about their occupation or whenever they can assume a symmetrical behavior of the other players. This also confirms the conclusions of [8], [9] about the Price of Anarchy of such scenarios being very high (potentially unbounded as the number of players increases). Intuitively speaking, all players are expected to blindly follow a sequential search, despite this being clearly non-optimal for the last players to enter the parking garage. Such a conclusion is also reached by these players themselves, however there is no better deviation that they can apply, since they are not aware of being in such unfortunate positions and may still consider to be among the first entered instead.

Incidentally, this also justifies the need for better collaborative strategies where the individual vehicles exchange information about their position and the occupancy they found in the parking garage [7]. From a game theoretic perspective, this can be framed as a further *cheap talk* game about the “state of the world” (meant as an occupation report of the parking garage made by vehicles ahead). However, this interesting approach would also require some validation mechanisms to prove that the report is not falsified [21].

## IV. Dynamic Simulation Tests

To expand on the obtained insight and analyze the described framework of a multi-storey parking garage further, with a realistic number of vehicles and a reasonable time window, we took a simulation approach. We considered an agent-based simulation scenario [20], whose underlying rules are similar to the ones described before in Section III. Each agent represents an individual vehicle, which can be assigned player-like characteristic of individual selfish behavior as per the game theoretic approach [6], [18].

For the sake of a simpler simulation, we modeled the players as only moving in one direction throughout the parking facility. Starting from the ground floor, they can decide to search the floor for a parking spot, or not to search and move a floor up. Once they reach the top floor, their choice is limited to searching or going down until they reach the ground floor again. We found out that this choice simplifies the investigations without significantly changing the conclusions that can be inferred; otherwise, we would have an unnecessary criterion to decide whether to move up or down every time, which would also lead to inefficient choices such as up-down loops.

We still consider the players to be driven by numerical utilities associated to the value $C_M$ for the cost of moving up or down, and the searching cost $C_S$. The simulation runs for an artificial “day” that is subdivided into 1000 individual time steps. At every step, the game (as the player “Nature”) randomly decides if a new agent enters or an existing agent leaves the parking garage, thereby emptying the occupied spot. Also for simplicity, we do not consider multiple arrival events, which is realistic since it is assumed that the entrance of the garage allows for one vehicle at a time. The chance of a new agent reaching the parking premises to enter at time $t$ is equal to $1 - t/1000$, i.e., it shifts gradually from 100% at timestep 1 to 0% at timestep 1000.

To control this environment without changing its dynamics, two additional restrictions are implemented. No more than $N_c$ vehicles can enter the multi-storey parking facility at the same time and no more than $N_t$ vehicles in total can enter the game in the entire simulation. Using these rules, the resulting environment matches a reasonable entry/exit process of a parking facility in a downtown area over one day, being mostly full during the daytime, while vehicles leave again in the evening so that the parking garage is empty by the end of the day. An example of how the occupation of the different floors of the parking facility looks over the course of one day can be seen in Fig. 1.

In contrast to the analytical model, here each player controlling an agent (vehicle) has access to a variety of

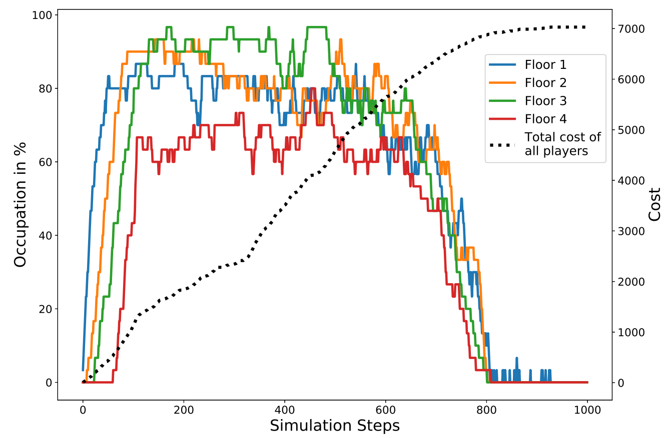


Fig. 1: A Parking Facility over the course of one day.

information on the current state of the game: for example, even though a player does not know the precise occupancy state of each floor, it makes sense to assume that it knows its time of entrance. Also, the current availability of free parking spots in the present floor may be known, e.g., being displayed at the entrance of each floor.[1] Thus, we can adapt the planned strategies to this side information that is common knowledge among the players, similar to that they also know the trend of arrival and every other general aspect of the game. The idea is to define different strategies using these information and compare the utility of vehicles playing the game.

We consider two particular *tests* to perform on this scenario. For both tests, we resort to a simulation of many game instances with different random generations. Averaging over multiple instances, we are able to gain evidence of how different strategies rank against each other under different conditions. The first investigation, called **Mobility test**, aims at analyzing the general impact of the readiness of each agent to change floor. Each player $j$ is assigned with a random *mobility value* denoted as $\mu_j$ ranging from 0 to 1, that influences the decision of changing floor, resulting in an agent having higher chance to keep searching in the current floor when the value is lower and preferring to be more mobile when the value is higher.

The formal specifications are as follows. Denoting by $L$ the number of levels, $f_i$ and $g_i$ the free and total parking spaces on level $i$ for $1 \leq i \leq L$, respectively, we assume that each player $j$ located at level $i$ follows this decision rule:

$$\begin{array}{ll} \textbf{search} & \text{if } \dfrac{f_i}{g_i} > \mathbf{r} + \dfrac{\mu_j - 0.5}{5} \\ \textbf{move} \text{ (up or down)} & \text{else} \end{array}$$

where $\mathbf{r}$ is a uniformly distributed pseudorandom number in $[0, 1)$. The cost incurred by each player is also accordingly increased by $C_S$ or $C_M$, respectively. If a parking spot is found, the agent terminates its run and pays the final

[1] The presence of available free spots at a given level does not necessarily prompt a player to search for that level immediately since it may also expect that other players will do so and this may result in a wasted effort.

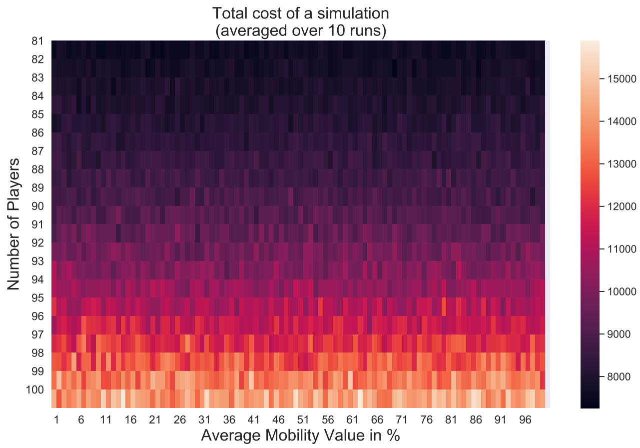


Fig. 2: Total utility vs. the number of users and the mobility value.

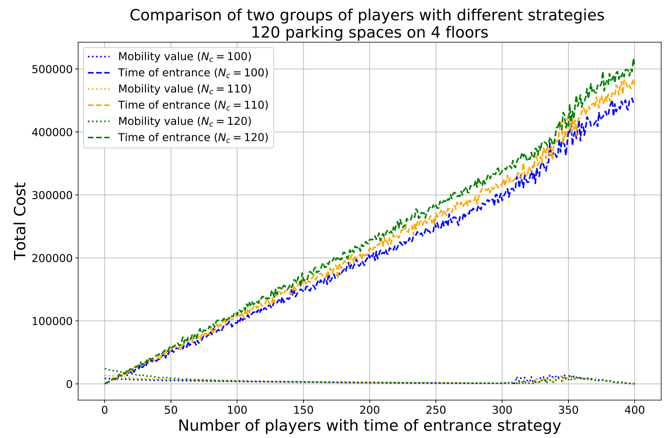


Fig. 3: Two groups of players play with different strategies and their total costs are compared under varying conditions.

cost (negative utility). For the sake of uniform numerical evaluations, in the following section we will choose the same value of $\mu_j$ for all the players.

The second investigation is instead based on the remark that, by looking at Fig. 1, one might assume that a player who frequents the parking facility is aware of the trend and purposely tries to play against it. To explore this, we developed the **Time of Entrance Test**, where we assume that players entering the parking facility at the beginning of the simulation are aware that the parking premises are likely empty and therefore search for a spot right away. As the day goes by, players prefer to move up a few floors before searching. In the evening, the tendency gradually shifts towards searching on lower floors again.

Thus, the selection rule of players when they are at floor $i$ changes according to time $t$ as follows. If $t < 200$:

$$\begin{array}{ll} \textbf{search} & \text{if } \frac{1}{20000} \cdot t \cdot (90 - 20i) < \mathbf{r} \\ \textbf{move} \text{ (up or down)} & \text{else} \end{array}$$

For $200 \leq t \leq 600$:

$$\begin{array}{ll} \textbf{search} & \text{if } \frac{1}{10} \cdot (9 - 2i) < \mathbf{r} \\ \textbf{move} \text{ (up or down)} & \text{else} \end{array}$$

and for $t > 600$:

$$\begin{array}{ll} \textbf{search} & \text{if } \frac{1000 - t}{40000} \cdot (90 - 20i) < \mathbf{r} \\ \textbf{move} \text{ (up or down)} & \text{else} \end{array}$$

where again $\mathbf{r}$ is a uniformly distributed pseudorandom number in $[0, 1)$.

## V. Numerical Results

We perform the previously devised tests by simulating a parking facility consisting of 4 floors with 25 parking spaces each, therefore $N_c = 100$ and we also consider that no more than $N_t = 400$ vehicles enter for one day. The cost values are chosen as per Section III, i.e., $C_M = 3$, $C_S = 7$.

As a possible way to understand the challenge of achieving an overall efficient allocation, we consider the following evaluation in the **Mobility Test**. We change the *Mobility value* of the players, reflecting the predisposition of players to change a floor over fighting for a spot in the present one. The result is displayed in a heatmap in Fig. 2. Since this plot shows the total utility of the players, the value is clearly increasing in the number of players. Yet, there is a utility increase whenever on average some of the players are willing to switch floors instead of lazily search for a space in the present one (which possibly ends up in searching a full floor). Still, having all the players moving around is not a good solution either, so there is clearly a trade-off involved, and only a fraction of the agents should change floor. On the one hand, this shows the need for a strategy that breaks the symmetry of the game. However, from a game theoretic perspective, this also highlights how the strategy of a sequential search is strictly dominant and thereby preferable if all the other players are willing to move to a different floor.

Fig. 3 directly compares the two approaches in the two tests. The results match the intuition that exploiting additional information such as the time of entrance and the general pattern of arrivals in the facilities dramatically improves the cost. Fig. 4 shows a comparison of different strategies. It is confirmed that the sequential searching strategy is generally better and this reflects its status as a strictly dominant strategy. In general, players with the strategy of alternating between searching and moving do perform very well.

## VI. Conclusions

Systematic solutions for vehicles management are key in smart mobility environments. In this paper, we investigated some scenarios related to the problem of efficient competitive search for a parking spot in a multi-storey garage. From several findings, it is confirmed that a sequential search

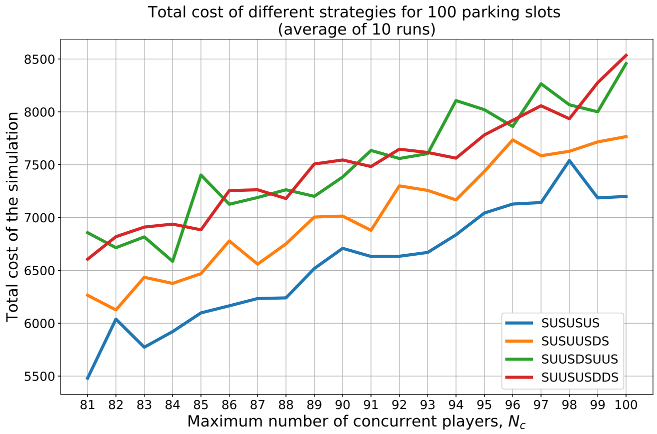


Fig. 4: Playing the game using the top strategies from the analytical model.

starting from the ground floor is the best strategy, but this also leads to a very inefficient game theoretic equilibrium. While this strategy appears to be the most favorable for selfish goals, it causes no desire for unilateral deviation towards more altruistic solutions. Indeed, it is not recommended to attempt to counter the strategy chosen by the majority of players. The performance of the individual agent gets significantly worse when players act as outliers compared to mimicking the strategy of the others.

However, this result opens the door to several challenges in the effort of finding more efficient distributed allocations. First of all, we identified that the exploitation of side information (and specifically the time of entrance in accordance to the typical occupancy pattern over a day) can be extremely beneficial for devising a better solution, even from a global perspective. Yet, even this finding does not solve the problem of the same strategy being indifferently promoted to all the users, therefore obtaining an inefficient Nash equilibrium. At the same time, randomizing the strategy or adopting inter-vehicle communication does not guarantee high efficiency either, and also poses the additional challenge of trusting other users. The search for an efficient solution still appears as an open problem, which is undoubtedly interesting.

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