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Editorial: Parking in the connected and automated era: Operation, planning, and management

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published in

Transportation Research Part C: Emerging Technologies
2021

DOI (link to publisher)

[10.1016/j.trc.2021.103115](https://doi.org/10.1016/j.trc.2021.103115)

document version

Publisher's PDF, also known as Version of record

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citation for published version (APA)

Xu, M., Inci, E., Chu, F., & Verhoef, E. T. (2021). Editorial: Parking in the connected and automated era: Operation, planning, and management. *Transportation Research Part C: Emerging Technologies*, 127, 1-3. [103115]. <https://doi.org/10.1016/j.trc.2021.103115>

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Contents lists available at ScienceDirect

Transportation Research Part C

journal homepage: www.elsevier.com/locate/trc

Editorial: Parking in the connected and automated era: Operation, planning, and management[☆]

1. Introduction

Recent technological developments in connected and automated technologies have enabled enormous innovations and possibilities in dealing with parking operation, planning, and management; including but not limited to parking reservation systems, parking autonomy, shared parking, smart parking systems, parking location choice, and parking space management systems. Emerging technologies have provided countless new opportunities to improve parking services. Although there are still uncertainties associated with their public acceptance, implementation, and governance, parking in the connected and automated era has already started to influence our daily travel patterns and mobilities. It also has a commendable impact on public transportation, urban land use, and perhaps the entire transportation system.

In the face of the connected and automated era, it is crucially important to investigate how to improve the functioning of parking markets by making use of innovative methods and technologies. We should also explore new mechanisms to improve our understanding of parking markets from an integrated perspective of operation, planning, and management. Thereby, it is also crucial to identify the acceptance level of the public.

Against this background, this special issue brings together some of the latest cutting-edge research that looks at parking from the perspectives of operation, planning, and management. There are seven papers that were selected from nearly 30 submissions. The papers contribute to parking research by investigating synergies and interactions that new technologies and mechanism can introduce to the parking systems. They cover a wide range of topics from smart automated parking system evaluation to empirical studies on acceptance of shared parking/smart parking, from data-driven parking system modeling to smart parking system designs under various scenarios, from parking management optimization to equilibrium analyses of incentive mechanisms for shared parking problems. The key contributions and features of the papers are summarized in the next section.

2. Contributed papers

In many cities around the world, there are more parking spaces than cars, which means that often parking spaces remain vacant for certain periods of time, although in certain locations parking demand is still higher than existing parking spaces in that specific area (Arnott et al., 2015; Inci, 2015; van Ommeren et al., 2021). Hence, parking space sharing has high potential in terms of societal impact, as well as profit opportunity. However, the main problem is uncertainty in demand, which may or may not meet the profit expectations of parking space owners. Yan et al. (2020) concentrate on this important and interesting problem. They analyze parking space owners' propensity to share their private parking spaces under conditions of uncertainty. Using a hybrid random-parameter logit-cumulative prospect theoretic model, they investigate the influence of sharing-scheme-specific (no sharing, fixed, flexible), person-specific and contextual factors on owners' willingness to share their parking spaces. In some sense, they unravel the acceptability of parking sharing under conditions of heterogeneity and uncertainty.

Considering the future of autonomous vehicles (AVs) with parking autonomy, alternative parking options become available as AVs can park at more distant locations away from the trip maker's destination. Su and Wang (2020) incorporate autonomous vehicle (AV)

[☆] This article belongs to the Virtual Special Issue on IG005577 - VSI: Parking.

users as both demand- and supply-side agents into their parking choice behavior analysis. They investigate the morning commute problem while explicitly modeling the AV parking choice behavior (i.e., by considering the possibility that AV commuters' can park at distant locations in a many-to-one network). They also explicitly consider the parking sharing scheme, in which the AV travelers can choose to park in public parking facilities at the city center and then lease their own parking space out, park at home, or park at a shared parking space. They then determine the day-to-day user equilibrium travel pattern with the parking choice prioritizations. They underline that multiple distant AV parking options, with staggered the commuters' departures, can alleviate bottleneck congestion. They also scrutinize the two critical factors in separating travel queues (i.e., the parking pricing and parking supply in the city center). They show that proper choice of differentiated parking charges/subsidies along with an appropriate choice of parking supply in the city center can minimize total queueing costs.

To approach the optimal parking management of connected autonomous vehicles (CAVs) in the presence of multiple parking lots within a given area, Wang et al. (2021) develop a continuous-time stochastic dynamic model, which incorporates interactions among parking garages. The time-dependent parking space availability is considered as the system state, while the dynamic price of parking is used as the control input. By regulating parking rates, the total demand for parking can be distributed among the set of parking lots under consideration. The authors further formulate an optimal control problem (i.e., a Bolza problem) with the objective of maintaining the availability of each parking garage at a desired level, which could potentially reduce traffic congestion as well as the fuel consumption of CAVs. They also conduct a series of numerical simulations taking into account various parking scenarios to show the effectiveness of their proposed approach.

Considering that fully automated vehicles can self-drive, they have the potential to avoid parking costs since the AV can drop the owner off at their destination, and then drive elsewhere to park. Levin et al. (2020) propose models to approach the choice of parking location when AVs reposition away from the traveler's destination. They present a modified static traffic assignment with a logit model for destination choice, in which AV passenger-carrying trips can create a second empty repositioning trip to an alternate parking zone. They formulate the traffic assignment as a variational inequality. Numerical results on the Chicago sketch network show the effects of AV market penetration, fuel costs, and parking fees on the number of repositioning trips, as well as the impacts of repositioning trips on network congestion. They further study the problem of adjusting zone-specific parking costs to influence the repositioning behavior. When zones have asymmetric parking infrastructure costs, optimized parking fees combined with empty repositioning can encourage AVs to park at cheaper locations, thus reducing the land used for parking at zones with high land value. This network design problem is formulated as a bi-level program. Simulation results on the Sioux Falls test network show that the adjusted parking costs are effective at reducing congestion caused by empty repositioning and encouraging more optimal parking choices for repositioning AVs.

Bahrami et al. (2021) consider the scenario that AV users may send their vehicles to cruise around the block or travel back home instead of parking. They investigate the AV users' parking choice in a downtown area by establishing a Wardrop equilibrium. They model the AVs parking choice problem in downtown areas as a fixed-point problem and propose an efficient method to solve it. They show that the equilibrium problem might have multiple solutions in which congestion and externalities are considerably different and provide a robust parking policy design formulation to recommend parking management policies to improve social welfare. The model considers that AVs can intentionally slow down to substitute cruising for parking, which can create severe congestion. Their analysis also highlights that time-based congestion pricing is the key factor to hinder AVs from cruising that exacerbates congestion. They note that the other types of congestion toll schemes, such as cordon-based or distance-based tolls, are not that effective in reducing congestion caused by AVs cruising instead of parking.

Different from the studies of Levin et al. (2020) and Bahrami et al. (2021), both of which present approaches for parking choice of AVs, Siddique et al. (2021) focus on the higher storage capacity of parking with self-parking and intelligent communication capabilities of AVs. They show how to maximize the number of AVs in a parking lot that assumes interfering cars could be moved out of the way by a centralized controller. They compare three types of parking lot design (limited egress, complete egress, and traditional lots) and provide optimal results for small lots with a single entry point, and offer heuristic methods (i.e., the puzzle-based parking algorithm) for larger lots. They recommend keeping the puzzle-based designs small to reduce the waiting time and the number of relocations. They show that, in small parking lots, it is possible to achieve on average 80% higher density than in traditional parking lots. Commercial garages can adopt the complete egress design to accommodate more cars in busy downtown areas, and 80% or less density is recommended to minimize the number of relocations.

Lai et al. (2021) take on a mechanism design approach in dealing with the shared parking problem. The multi-unit exchange mechanism presented in their paper aims to improve the efficiency of the use of private parking spaces in the morning commute. Since person-to-person exchange is not easy to implement, they propose a mechanism in which agencies oversee parking lots on behalf of property owners. An e-platform assigns a parking space quota to each agency from each other agency and sets transfer prices among them. Before starting their commute, the commuters book parking spaces via the platform. Coming up with a quota and price scheme for each agency is a daunting task since such a mechanism must ensure that agencies do not have an incentive to make transactions out of the platform because otherwise the platform would eventually vanish. Lai et al. (2021) achieve this by employing well-known stability and core notions from mechanism design. In the end, the parking sharing mechanism mimics a competitive equilibrium, and it is stable as it will be in the core. The paper also allows for some real-life complications such as booking cancellations. Finally, to illustrate the performance of the mechanism, a simulation of the parking market of Guangzhou city is presented.

3. Summary

Parking problems are complex and involve sophisticated issues of planning, operation, and management. That is why they have attracted considerable attention from different research areas including but not limited to transportation, economics, urban planning,

and operations management. Existing work mostly concentrates on efficient operation and effective management of parking spaces (e. g., reducing cruising time, mitigating parking-related congestion, and improving parking services). With the development of connected and automated technologies, further studies are needed to develop innovative parking services and to understand their deployment and potential impacts on dealing with parking challenges. The papers in this special issue aim to achieve this goal by presenting some of the new approaches, models, visions, and findings related to parking markets in the connected and automated era. Some of them emphasize the importance of AVs that have parking autonomy as well as their potential impacts. Others offer solutions to parking space sharing, analyze its societal impact, and investigate the potential of dynamic parking pricing. Yet others concentrated on the AVs' choice of parking location, puzzle-based parking design, and mechanism design for shared parking problems.

All papers in the issue have useful approaches and we hope that they provide benefit to the practical applications in the parking markets. To keep up with the rapid development of technologies and innovations in the connected and automated era, we still need more research analyzing parking planning, operation, and management, need more new modeling approaches and applications of smart parking systems including shared parking mechanism (Xiao et al., 2018). We should continue to explore the impact of these technologies and innovations on better parking pricing and revenue management. We should keep on investigating how to use them in economic analysis of the design of private, public, and hybrid parking markets in the presence of contemporary challenges in urban transport. We still need more empirical case studies and behavioral modeling of parking markets. Last but not least, we should continue to explore the interactions between parking markets and other markets. We hope that future research will come to deepen our understanding of how emerging technologies can contribute to the functioning of parking markets. We wish that this special issue induces more parking studies for the benefit of the public and our society.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

As the co-editors of this Special Issue, we would like to thank all authors for submitting their best piece of work to this special issue, the referees for their time and efforts in reviewing the received manuscripts, and especially Professor Yafeng Yin (ex-editor-in-chief) for his genuine interest in the topic and his tremendous support to this special issue.

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