DESIGN PARKING FACILITIES FOR AUTONOMOUS VEHICLES

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Introduction

Parking is an important part of transportation planning because a typical vehicle spends 95% of its lifetime sitting in a parking spot (Mitchell, 2015). The increasing need to store vehicles has transformed a lot of valuable real-estate into parking garages in many countries. In the United States, approximately 6,500 square miles of land is devoted to parking which is larger than the entire state of Connecticut (Chester et al., 2011; Thompson, 2016). Allocating valuable land to parking increases renting costs and parking acquisition costs in major downtown cores. One example is Hong Kong where the average cost of one parking space is as high as $ 180,000 USD (South China Morning Post, 2015). Realizing the high social cost of parking provision, Autonomous Vehicle (AV) industry leaders are rethinking how to reduce the parking footprint by converting traditional parking lots into automated parking facilities that can store more AVs (compared to regular vehicles) in smaller areas. In this study, we investigate the optimal design and management of such facilities.

AVs can reduce the parking footprint in several ways. As vehicles become driver-less, the passengers no longer need to be physically present in car-parks. Driver-less AVs drop off their passengers at the parking entrance (or at a designated drop-off zone) and head to a spot chosen by the car-park operator.
In this automated parking system, the average space per vehicle is estimated to decrease by 2 square meters per vehicle because the driving lanes become narrower, elevators and staircases become obsolete, and the required room for opening a vehicle's doors becomes unnecessary (see Fig. 1) (TechWorld , 2016).

Motivated by the benefits of AV parking and its impact on revitalizing valuable real-estate, auto makers are collaborating with cities to create the first generation of AV parking facilities. Audi's Urban Futures Initiative is among the programs that are implementing a pilot to measure the impact of AV parking on land restoration. The pilot is estimated to save up to 60% in parking space by 2030 which is equivalent to $100 million USD in the district of Assembly Row which is the focus of the project (DesignBoom, 2015). Tesla, another leader in AV technology, is also improving parking by offering an auto-pilot system called "Smart Summon" which allows the vehicle to navigate complex environments and parking spaces whenever summoned by its owner. Such auto-parking systems in AVs will pave the way for the next generation of AV parking facilities with improved space efficiency.

An essential strategy to increase car-park space efficiency (in addition to removal of elevators, etc.) is to stack the AVs in several rows, one behind the other as shown in Fig. 1(b). While this type of layout reduces parking space, it can cause blockage if a certain vehicle is barricaded by other vehicles and cannot leave the facility. To release barricaded vehicles, the car-park operator has to relocate some of the vehicles to create a clear pathway for the blocked vehicle to exit. The extent of vehicle relocation depends on the layout of the car-park which should ideally be designed so that parking occupancy (i.e., number of vehicles in the car-park) is high and vehicle relocation is low.

The layout of the car-park has a great impact on space efficiency. Existing layouts divide the car-park into a number of islands and roadways. The islands are used to store vehicles while the roadways separate the islands and allow vehicles to maneuver when searching for a desirable spot. To ensure that no vehicle gets blocked, islands hold no more than two rows of vehicles in conventional car-park designs (see Fig. 1(a)) which leads to waste of space. With AV technology, however, the islands can have more than two rows and the roadways can be narrower. An eminent research question that arises is: How should we design AV parking facilities that store the maximum number of AVs with minimal relocations? To answer this question, we pursue the following objectives throughout this study:

- We present a model to find the optimal layout of a parking facility for AVs.
- We define a relocation strategy that ensures a smooth retrieval of any AV that is summoned by its user.
- We find the maximum number of AVs that fit into a car-park with given dimensions.
- We quantify the potential parking space reduction when the car-park is exclusively designed for a given number of AVs.

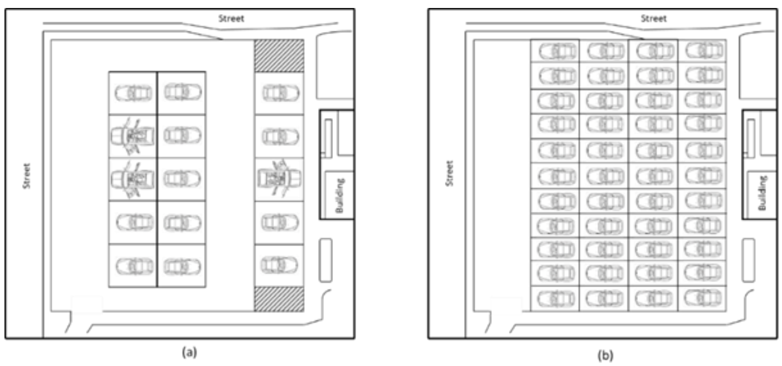

Figure 1. (a) Conventional parking design, (b) autonomous vehicle parking design.

AVs could have a great impact on the design of car-parks in the future. While existing parking facilities have islands with only two rows of vehicles, future designs tailored for AVs can have multiple rows of vehicles stacked behind each other. The multi-row design can lead to blockage of some vehicles which can be handled if the operator moves the vehicles in the facility in an optimal way. Naturally, the number and pattern of relocation changes with the layout of the car-park. This paper investigates the problem of finding the optimal car-park layout design that minimizes relocations while fitting a given number of vehicles in the car-park.

Finding the optimal layout can have many social benefits. For one, we find that AV car-parks can decrease the need for parking space by an average of 62% and a maximum of 87%. This revitalization of space that was previously used for parking can lead to social benefits when car-parks are converted into commercial and residential land-uses. Second, our study captures the influential factors that impact the optimal layout of car-parks for AVs. For instance, we show that square-shaped car-parks can enhance several measures of effectiveness. Finally, we capture the impact of the demand (for parking) on the optimal car-park layout. We show that when demand is low, the car-park has only two-column islands and when demand is high, the optimal layout becomes more complex.

This study focuses on the high-level strategic design of car-parks by finding the optimal layout under several assumptions that are valid for higher level planning. For finer level operational planning, however, we need to make adjustments to the model. We name some of these modifications that require further research.

For finer level operational planning, a new model is required that considers individual characteristics of each vehicle including arrival time, planned departure time, and vehicle size. Knowledge of departure times can significantly influence how the vehicles are arranged in the car-park. Ideally, the vehicles with earlier departure times should not be buried deep in the islands. They should instead be on top of the islands for a fast retrieval when they are summoned. Users can provide their departure times to the car-park operator using any smart platforms such as a mobile app.

In the model, we assume that parking demand is constant and fixed throughout the planning period which leads to one optimal layout for the car-park. In practice, however, this optimal layout can change within the day according to dynamic parking demand. For example, the facility can have one layout in the morning and another layout in the afternoon. In future research, it would be valuable to derive the optimal dynamic layout of the car-park according to changes in demand.

We present a model for cases where the car-park is a rectangle with given dimensions. A clear-cut rectangular car-park may not always exist in reality. Hence, it is important to extend the model to solve other irregular car-park profiles as well. It is also important to consider the optimal layout in multi-storey buildings where the floors are connected either through a elevators (for vehicles) or ramps.

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