PARKING FACILITY LOCATION AND USER PRICING IN THE ERA OF AUTONOMOUS VEHICLE OPERATIONS

by

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Dedicated to my beloved parents Ayoub and Fatemeh, and my dearest sister, Reihaneh

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ABSTRACT

Parking continues to pose a frustrating problem for travelers and commuters at large metropolitan areas. Despite a significant number of parking spaces, as they struggle to find appropriate parking spots and in doing so, waste enormous amounts of time and money finding and using available parking. With the looming advent of autonomous vehicles (AVs), there is a great opportunity to identify sustainable solutions to the parking problem because AV travelers can travel directly to their destinations to drop them off and then proceed to park at a relatively distant but lower-priced parking facility. Hence, the parking demand in downtown areas is expected to drop significantly as the market penetration rates of AVs increase. This could lead to the decommissioning and repurposing of some existing parking facilities in the downtown areas. However, this raises some social inequity concerns regarding the parking needs of human-driven vehicle (HDV) travelers particularly if the parking facilities are decommissioned at a time of low AV penetration. This thesis presents and demonstrates a comprehensive bi-level optimization framework for locating/relocating/decommissioning, and pricing parking facilities to serve a mixed fleet of AVs and HDVs in long-term. In the upper-level, the transportation decision-maker seeks to minimize the total travel cost of the travelers, to maximize the total parking fee revenues, and to maximize the monetary benefits of decommissioning and repurposing the existing parking facilities. In the lower-level, the AV and HDV travelers seek to minimize their travel cost given the decisions made by the transportation decision-makers in the upper-level. The problem is formulated mathematically as a mixed-integer nonlinear program and is solved using a hybrid approach consisted of machine learning and optimization heuristics. The numerical results indicate that the algorithm is capable of solving the problem in an efficient manner. It is found that as the budget for constructing new parking facilities in the outskirts increases, total cost of the travelers increases since the downtown parking facilities can be decommissioned at faster paces. Also, even without any new parking facility construction, it is possible to decommission some of the existing parking facilities at a time of high AV penetration due to the AV's requirement of smaller parking spaces compared to HDVs. Further, we found that in high construction budget levels, it is recommended to construct large-sized parking facilities in the outskirts but relatively close to the downtown area, and then, construct small-sized parking facilities in relatively farther locations to fulfill the parking needs of AVs. The numerical results also suggest that similar parking facility decommissioning

plans are proposed when the monetary benefits of decommissioning each parking facility is greater than a relatively low threshold. Further, despite the increases in the total travel demand, higher AV penetration rates result in lower total travelers' costs and parking fee revenues.

NOTATIONS

Sets

$\boldsymbol{N}$	Set of nodes
$\boldsymbol{A}$	Set of arcs ($(i, j) \in A$)
$\boldsymbol{T}$	Set of time periods ($t \ \in T$)
$\boldsymbol{M}$	Set of user groups (HDVs: $m = 1$, AVs: $m = 2$)
$\tilde{\boldsymbol{G}}$	Set of user sub-groups (Parking required: $\tilde{g} = 1$, Parking not required: $\tilde{g} = 2$)
$\boldsymbol{R}$	Set of origins ($r \in R$)
$\boldsymbol{S}$	Set of destinations ($s \in S$)
$\boldsymbol{W}$	Set of origin-destinations ($w = (r, s) \in W$)
$\boldsymbol{K}$	Set of candidate parking facility nodes locations ($k \in K$)
$\boldsymbol{K'}$	Set of existing parking facility nodes locations ($k' \in K'$)
$\boldsymbol{N^D}$	Set of dummy nodes
$\boldsymbol{A^D}$	Set of dummy links

Parameters

$\boldsymbol{\xi_1}$	Relative weight of total system travel time in the upper-level objective function
$\boldsymbol{\xi_2}$	Relative weight of total parking fee revenues in the upper-level objective function
$\boldsymbol{\xi_3}$	Relative weight of monetary benefits of decommissioning and re-purposing existing parking facilities in the upper-level objective function
Δ^{t}	Time-specific factor for obtaining the present value of a cost occurring in period t with considering the period duration
$\boldsymbol{\sigma_{0,i,j}^{t}}$	Free-flow travel time of link (i, j) in period t
$\boldsymbol{\chi_{i,j}^{t}}$	Capacity of link (i, j) in period t
$\boldsymbol{\varphi^{t}}$	Maximum acceptable HDV-AV travel cost ratio (HATCOR equity constraint)
$\boldsymbol{\upsilon^{t}}$	Maximum acceptable HDV travel cost ratio (HTCOR equity constraint)
$\boldsymbol{g_{k}^{s,t}}$	Last-mile travel time from parking facility node k to destination s in period t
$\boldsymbol{\theta_{m}^{t}}$	Value of time for user group m travelers in period t ($/hr.)
$\boldsymbol{\bar{\theta}}$	Relative value of in-vehicle travel cost compared to operation cost for AV travelers
$\boldsymbol{\Psi^{t}}$	Level 1 parking fee in period t ($)
$\boldsymbol{\varrho}$	Maximum fee level of each parking facility
$\boldsymbol{\varsigma}$	Maximum capacity level of parking capacity
$\boldsymbol{q_{r,s,m}^{t,g}}$	Travel demand of user sub-group g of group m travelers of origin-destination (r, s) in period t
$\boldsymbol{f_{\ k}^{\ t}}$	Construction cost of level 1 parking facility at node k in period t
$\boldsymbol{\omega_{k}^{t}}$	Monetary gain in period t by decommissioning the existing parking facility k
$\boldsymbol{\gamma_{k}^{t}}$	Capacity of level 1 parking facility k in period t
$\boldsymbol{B^{t}}$	Construction budget for period t
$\boldsymbol{\iota_1}$	Construction-capacity factor for deriving the construction cost of parking facilities
$\boldsymbol{d_{1}^{s}}$	Dummy node representing destination node s for sub-group 1 HDV travelers
$\boldsymbol{d_{2}^{s}}$	Dummy node representing destination node s for sub-group 1 AV travelers
$\boldsymbol{b_{i,m}^{s,t}}$	Auxiliary variable for flow conservation constraint of HDVs
$\boldsymbol{\bar{b}_{i,g}^{s,t}}$	Auxiliary variable for flow conservation constraint of AVs (phase 1)

$\bar{\bar{b}}_{i,2}^{d_2^s,t}$ Auxiliary variable for flow conservation constraint of AVs (phase 2)

$\aleph$ Factor that accounts for AV's requirement of smaller parking space compared to HDV (AV parking space reduction factor)

Variables

$\boldsymbol{Z^U}$	Objective function of the upper-level problem (The transportation decision makers)
$\boldsymbol{\Pi_1}$	Cost of total system travel time
$\boldsymbol{\Pi_2}$	Total parking fee revenues
$\boldsymbol{\Pi_3}$	Monetary benefits of decommissioning some existing parking facilities
$\boldsymbol{\Gamma_k^t}$	Parking facility k revenues in period t
$\boldsymbol{Z_L}$	Objective function of the reformulated lower-level problem
$\boldsymbol{\sigma_{i,j}^t}$	Travel time of link (i,j) in period t
$\boldsymbol{v_{i,j}^t}$	Traffic flow of vehicles traversing link (i,j) in period t
$\boldsymbol{x_{i,j}^t}$	Traffic flow of HDVs traversing link (i,j) in period t
$\boldsymbol{y_{i,j}^t}$	Traffic flow of AVs traversing link (i,j) in phase 1 in period t
$\boldsymbol{y_{i,j,g}^{s,t,1}}$	Traffic flow of user sub-group g AV travelers traversing link (i,j) in period t that have destination s in phase 1 of their travel
$\boldsymbol{y_{i,j,1}^{d_2^s,t,2}}$	Traffic flow of AVs traversing link (i,j) in phase 2 in period t that have already dropped off their travelers in destination s
$\boldsymbol{x_{i,j,g}^{s,t}}$	Traffic flow of user sub-group g HDV travelers traversing through link (i,j) with destination s in period t
$\boldsymbol{u_{r,s,m}^{t,g}}$	Travel cost of the sub-group g of class m travelers for origin-destination (O-D) pair (r,s) in period t
$\boldsymbol{\lambda_{i,g}^{s,t,1}}$	Travel time from node i to destination s for a sub-group g AV traveler in period t
$\boldsymbol{\lambda_{i,1}^{d_2^s,t,2}}$	Travel time from node i to the dummy node d_2^s for AVs that have already dropped off their travelers at destination s in period t
$\boldsymbol{\pi_{i,g}^{s,t}}$	Travel time from network node i to destination s for sub-group g HDV travelers in period t
$\boldsymbol{\delta_k^t}$	Binary variable which equals to 1 if the parking facility node k is available for parking in period t, and 0 otherwise.
$\boldsymbol{Q_k^t}$	Parking facility k capacity level in period t ($Q_k^t \in \{0,1,\dots,\varsigma\}$)

$\boldsymbol{H_{k,m}^{t}}$	Fee level of parking facility k for user group m travelers in period t $H_{k,m}^{t} \in \{0,1,\dots,\varrho\}$)
$\boldsymbol{\rho_{k}^{t}}$	Additional perceived cost that prohibits travelers from using parking facility k in period t

LIST OF ABBREVIATIONS AND ACRONYMS

MUL	Modified Upper-Level problem
AV	Autonomous Vehicle
HDV	Human-Driven Vehicle
HATCOR	Human-Driven Vehicle to Autonomous Vehicle Travel Cost Ratio
OD	Origin-Destination
PFLP	Parking Facility Location Problem
MINLP	Mixed-Integer Nonlinear Problem
NP-Hard	Nondeterministic Polynomial-time Hard problem
AVPR	Autonomous Vehicle Penetration Rate

CHAPTER 1. INTRODUCTION

1.1 Background and motivation

At metropolitan areas, parking infrastructure serves as a critical element of the transportation infrastructure and network operations, and plays a vital role in the efficiency and comfort of urban travelers and commuters. The National Household Travel Survey (NHTS) suggests that 91 percent of travelers in the United States use personal vehicles and these travelers need to park their vehicles in a parking facility. (NHTS 2020). On-street and off-street parking facilities typically exist at downtown areas to address the parking needs of urban travelers and these facilities occupy a significant amount of valuable land space in the downtown areas (Kimmelman 2012; Plumer 2020). For example, in downtown Los Angeles, parking facilities occupy as much as 1,400 soccer fields (Rowland 2019). Yet still, finding an appropriate parking location in downtown areas remains a challenge for travelers that drive. While Los Angeles has the world's highest parking space density (Greene 2016; Shoup 1997) and parking covers at least one-third of the land area (Ben-Joseph 2012; Smart Cities Connect 2017), it also has one of the worst traffic congestion conditions worldwide, as suggested by the INRIX 2017 Global Traffic Scorecard (INRIX 2017).

Another example of a metropolitan area, New York City, has more than five million parking spaces (Op-Ed 2020). However, a recent (2017) survey revealed that travelers in that city spend on average 107 hours annually cruising for parking spots, costing each traveler more than $2,200 annually in terms of wasted time, fuel, and emissions (McCoy 2017). Such serious parking problems are not only prevalent at numerous urban areas, but also can be attributed in part to the inefficient design of parking facility networks in terms of their location and capacity (Peters 2017). The literature on parking policy suggests that further measures are required concerning the parking ease of access, walk time, and fees of parking facilities (Long 2013; MRSC 2020; Parmar et al. 2020). Hence, it is important to develop a modeling framework that helps manage both parking supply and demand by identifying optimal parking facility locations and pricing structures.

The emergence of autonomous vehicles (AVs) not only makes it imperative but also provides a valuable opportunity to revisit the problem of parking facility location and capacities at existing downtown areas. The capability of AVs to travel without a driver enables the traveler to disembark from the AV at their destination and dispatch it to park at any location which could be distant from the downtown area. Therefore, for travelers in large metropolitan areas, AVs can help address their parking-related anxieties and reduce the often significant out-of-vehicle travel time spent between the parking facility and their destination. For this reason, it is expected that the downtown parking demand will drop significantly as the AV market penetration rates increase (Kellett et al. 2019). Simons et al. (2018) project that the demand for parking in downtown Cleveland would drop by up to 66 percent by the year 2035. The shifting of existing parking to outlying areas of the city can free up valuable land space in metropolitan downtowns that could be used for other uses that enhance business productivity or quality of life such as recreational facilities, commerce, and active transit modes (Kellett et al. 2019; Plumer 2020; Soteropoulos et al. 2018; Stead and Vaddadi 2019; Yigitcanlar et al. 2019). For this reason, urban planning paradigms that encourage re-design of parking facility locations and capacities can be beneficial.

While this optimistic viewpoint maintains that the quality of land use in the downtown areas will be improved by decommissioning the existing parking facilities in the future, there is also a pessimistic view. This viewpoint states that AVs will still use downtown parking spaces extensively in the future and the growth in vehicle ownership will even worsen the downtown parking conditions (Papa and Ferreira 2018; Stead and Vaddadi 2019). This highlights the role of transportation agencies in developing policies that help to improve both the land use quality, and parking conditions in the downtown areas. The transportation agencies and other decision makers in the private sector need to know the optimal timeline for decommissioning the existing downtown parking facilities, the optimal locations and timelines for constructing new suburban parking facilities, and the optimal parking pricing at such facilities in the long-term.

It is generally agreed that the advent of AVs will impact social equity, for example, AVs can improve social equity by satisfying the commuting needs of vulnerable social groups whose members cannot own or drive a vehicle (Fleming 2018; Milakis et al. 2017). However, AVs can also have negative impacts on social equity, due to their higher prices, as they will be relatively more accessible to higher-income earners, at least at earlier stages of their availability (Milakis et al. 2017). Hence, notwithstanding the efficacy of AVs to finally address the persistent conundrum of urban parking, this emerging mode could raise issues related to social inequity. As AV travelers prospectively dispatch their vehicles to distant parking facilities to park at a lower cost compared to existing downtown parking, not only will they spend far less on parking but also their AVs will spend some time back in the traffic stream on the way to the distant parking. That would cause increased congestion and thus impose higher travel times to all the network users including HDVs. Further, HDVs that patronize the relocated parking facilities may incur longer travel times to reach these locations or to travel between these parking locations and their destinations. The problem can be exacerbated if such parking location shifts are implemented abruptly with little or no transition period. To address the social equity issue, the transportation decision makers will need not only to gradually implement the optimal parking construction plan but also to implement the differentiated parking pricing scheme, i.e., charging different parking fees to AV and HDV travelers to address the potential inequity of shifting parking facilities during transition period.

This thesis provides a methodology with which the transportation decision makers can efficiently address these issues. Generally, the methodology determines the optimal locations and capacities that are associated with the urban network parking facility redesign over a given planning horizon. Specifically, this redesign involves the gradual construction of new parking facilities at selected outlying areas of the city, and the decommissioning of selected existing parking facilities at downtown locations. Further, the methodology provides a long-term parking pricing strategy that maintains social equity among AV and HDV travelers (Tabesh et al. 2020). The diagram shown below (Figure 1) illustrates how different aspects of the parking design problem impact each other.

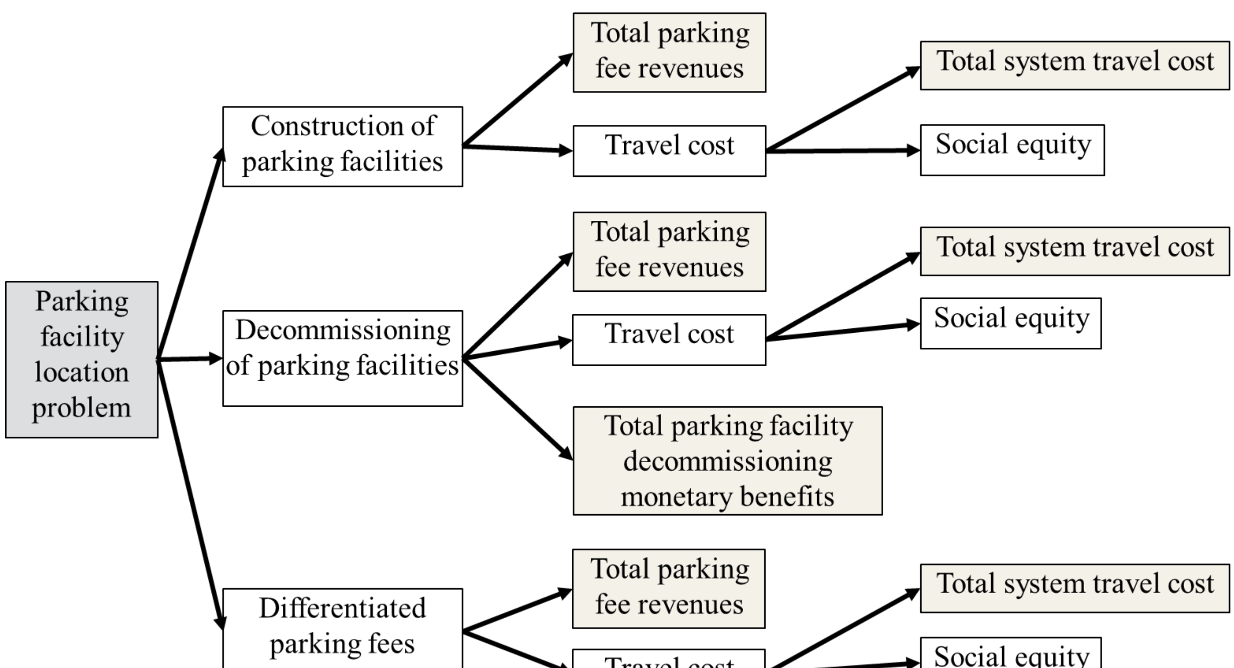


Figure 1. Parking facility location problem - attribute diagram

The intended contributions of this research are twofold. First, the study develops a bi-level multi-period framework where the transportation decision makers seek to minimize the total system travel time and to maximize the total parking fee revenues and the benefits of decommissioning and re-purposing the areas occupied by existing parking facilities. The control decisions are the (i) timings, locations, and capacities of the new off-street parking facilities, (ii) parking fees for AV and HDV travelers in each active off-street parking facility, and (iii) timings and locations of the existing off-street parking facilities to be decommissioned in order to utilize urban land more efficiently. Second, the study develops an optimal location-based differentiated parking pricing strategy for a traffic stream comprised of AVs and HDVs. The pricing strategy is constrained by the equity-motivated desire to keep the HDV-AV travel cost ratio (HATCOR) to a pre-specified threshold across the periods. The HATCOR is calculated by dividing the travel cost of HDV travelers by that of AV travelers for each origin-destination and is used as a measure to maintain equity (Tabesh et al. 2019a).

1.2 Organization of the dissertation

This thesis consists of six chapters. Chapter two provides a comprehensive literature review of the studies in two relevant areas, namely (i) AV parking impacts on traffic, and (ii) parking facility location problems. Then, the gaps in the literature in each of these two areas, and how this dissertation addresses them is illustrated. Chapter three addresses the methodology of this study which includes the preliminaries and assumptions, and also the mathematical formulation. Chapter four illustrates the solution methodology used in this study which is an adapted meta-heuristic algorithm. In chapter five, we present numerical results and discussions. Also, this chapter illustrates the effectiveness of the developed framework to address the parking-related issues of the downtown areas in the long term. Chapter six summarizes the thesis, highlights its findings and makes conclusions from the findings, identifies the study limitations, and provides directions for future research.

CHAPTER 2. LITERATURE REVIEW

In this chapter, the academic literature on (i) the parking facility location problem (PFLP) and (ii) AV parking impacts on traffic are discussed.

2.1 Literature on PFLP problem

Regarding the first group, although there exists a vast body of literature on the general facility location problem in transportation (Melo et al. 2009; Zanjirani and Masoud Hekmatfar 2009), only a few studies have specifically addressed the parking facility location problem (PFLP). In most of the early PFLP studies, the user equilibrium of the travelers and the impacts of new parking facility construction on the traffic congestion were not considered (Aliniai et al. 2015; Chiu 2006; Farzanmanesh et al. 2010; Jelokhani-Niaraki and Malczewski 2015; Kazazi Darani et al. 2018) and most of these studies used multi-criteria decision-making frameworks. For example, Jelokhani-Niaraki and Malczewski (2015) provided a holistic multi-criteria framework to determine the best locations for constructing new parking facilities. They combined the GIS and multi-criteria decision-making techniques to provide an efficient method based on factors such as the adjacent population to a proposed location, the proposed location's land size and its acquisition cost, and the average distance of the proposed location to main streets, public transportation stations, and commercial and recreational activity centers. One important advantage of this study is to consider various criteria for selecting a parking facility location. However, one limitation of this study which is mutual for this line of research is that the actual response of the travelers to the new proposed parking facility locations cannot be captured. Aliniai et al. (2015) also used an integrated GIS and multi-criteria decision-making methodology to investigate this problem considering various criteria including the average distance of the proposed location to the administrative, commercial, and recreational centers, the acquisition cost of the proposed land, and suitability of the proposed land. The "average distance to the important centers" criterion was assigned the highest weight in that study. Further, the land suitability in that study was defined based on the distance from critical facilities such as hospitals and historical sites. The authors concluded that new parking facility construction must be accompanied by travel and parking management strategies to ameliorate the network efficiency.

The paper by Farzanmanesh et al. (2010) is another study that integrated GIS and multi-criteria decision-making methods. In that study, criteria such as the proposed parking location distance to trip-attracting locations, distance to main streets, and the adjacent population were considered to determine the optimal locations for constructing new parking facilities. Employed using a similar approach, Kazazi Darani et al. (2018) tackled the PFLP problem with multiple economic, social, and environmental considerations including the population density and traffic congestion, and air pollution close to the candidate parking location, and the distance to public places. The last criterion was assigned by experts, the highest weight (Ben-Joseph 2012). While this line of research has broken new ground in the PFLP by introducing practical frameworks that can be deployed by the transportation decision makers to locate the parking facilities, they are unable to determine the "optimal" parking facility locations.

There also exist other PFLP studies that deployed optimization methods that did not consider traffic congestion. For example, Chiu (2006) introduced a multi-objective optimization program for the PFLP. This paper's research goals which appears to be one of the first PFLP studies in the literature include the minimization of the construction, operation, and maintenance costs of the parking facilities, minimization of the total walking costs of travelers, and maximization of the total parking "demand coverage". Each parking facility can provide service to a certain group of travelers who therefore, consider the walking distances acceptable from that parking facility location to their destinations. The parking demand coverage is a critical criterion in this line of work which has been also used in a PFLP paper by Eskandari and Shahandeh (2018). In this multi-objective optimization study, a flow-capturing model was introduced to model the parking choices of the travelers in a static context. The aforementioned studies identify the optimal locations for constructing new parking facilities but none of them considered the impacts of constructing proposed parking facilities on traffic congestion, and the actual route choices and parking choices of travelers (i.e., the traffic assignment) after the parking construction.

Some recent PFLP studies have considered the traffic assignment of the travelers, and hence, could be used to investigate the impacts of the proposed parking facility locations on the traffic congestion. Du et al. (2019) studied the PFLP for morning travelers considering traffic equilibrium conditions and parking cruising. Their objective is to minimize the total queuing delay of the travelers, and in their case study, they determined the optimal on-street and off-street parking locations in a working area with a few blocks. Shen et al. (2019) also addressed the PFLP considering the dynamic traffic assignment of the travelers seeking to minimize the CO_2 emissions. A relatively small urban area with a few blocks was considered as the case study as the authors state that their proposed framework can evaluate up to seven (7) candidate parking facilities. While these studies have provided significant contributions to the literature, they do not provide a long-term construction plan of the parking facilities. Further, they also do not consider the possibility of decommissioning the existing parking facilities for more efficient land-uses.

2.2 Literature on AV parking impacts on traffic

The second group of literature which is reviewed in this chapter deals with the AV parking impacts on traffic. A traffic assignment model was proposed by Zhang et al. (2019) for a fleet of AVs with parking choices to fill the gap in the simultaneous analysis of route and parking choices of AV travelers. They found that individual travelers can decrease their travel costs by using AVs instead of HDVs, while the traffic congestion can be worsened due to the empty trips their AVs make to find appropriate parking spaces. They also indicated that the AV traffic patterns are highly sensitive to factors such as the value of time, parking pricing, and parking availability.

Zhang et al. (2020) assessed the overall societal impacts of AVs considering the AV parking patterns by proposing combined traffic and economic equilibrium models. That study also indicated that AV parking patterns can worsen the traffic conditions, and hence, result in substantial social welfare losses due to fewer completed journeys and increased travel costs. According to that study, the transportation decision-makers need to provide more parking spaces in downtown areas if parking fees do not decrease significantly at locations farther from the downtown area. Conversely, if the parking fees decrease sharply when the distance to the downtown increases, more parking spaces are needed in the farther locations. The findings of that study are in line with those of Liu (2018) who jointly modeled the departure time and parking location choices of AV travelers. Both of these studies used dynamic equilibrium analysis to investigate the commuting problem for a single bottleneck under fully-AV traffic environments. Although these papers provide keen insights into the parking behavior of AV travelers, they all assume that the entire vehicle fleet is autonomous. In other words, the impacts on the HDV travelers' travel times and parking behavior was not investigated. Further, they do not consider the long-term impacts of the AV growth on the transportation and parking system, whereas in practice, the AV penetration rates will be expected to increase (Du et al. 2020). Finally, none of the current studies investigated the long-term impacts of new parking location policies.

2.3 Summary of the Literature Reviews

This chapter reviewed the literature on the parking facility location problem and also studies that have considered the impacts of AV parking on the performance of the transportation network. While these studies provide keen insights into the parking issues in downtown areas, there are some research gaps in each of these groups that need to be addressed. Most importantly, this dissertation combines the contexts of parking facility location problem and AV parking impacts on traffic to provide a comprehensive framework that can be used to address the parking dilemma in the future. Besides, while the current literature deals with the impacts of AVs on travelers' parking choices and performance of the transportation network, however, the long-term impacts on a network with mixed vehicle fleets of AVs and HDVs, which will be the case in practice for a long term, have not been considered. Table 1 summarizes the related papers and illustrates a comparison between those and this thesis.

Table 1. Literature review: A comparison of past work

Context	Study	Subject	User equilibrium	Fleet	Different parking fees in different locations	Parking decommissioning
AV parking impacts on traffic	Zhang et al. 2019	Traffic assignment for AVs with parking choices	yes	AV	yes	no
	Zhang et al. 2020	Integrated transport and economic equilibrium model	yes	AV	no	no
Parking facility location problem (PFLP)	Shen et al. 2019	PFLP based on the environmental costs	yes	HDV	no	no
	Du et al. 2019	PFLP based on the total travelers' queuing delay	yes	HDV	no	no
	Eskandari 2018	PFLP on the urban network with multiple objectives	no	HDV	no	no
	Jelokhani-Niaraki 2015	Multi-criteria spatial decision support system for PFLP	no	HDV	no	no
	Aliniai et al. 2015	Multi-criteria PFLP	no	HDV	no	no
	Ni et al. 2013	PFLP based on the optimal total social costs	no	HDV	yes	no
	Chiu 2005	Location model for allocating parking facilities	no	HDV	no	no
	This Study	Locating and pricing parking facilities in a congested network with mixed fleets of AVs and HDVs	yes	AV and HDV	yes	yes

CHAPTER 3. METHODOLOGY

This chapter presents the methodology of this dissertation. It starts with an introduction that summarizes the bi-level framework that has been used. This is followed by some preliminary settings and assumptions that were made in the analysis. Then, the upper-level and lower-level models of the bi-level framework are described in detail.

3.1 Introduction

The problem is formulated as a bi-level program (Figure 2). The bi-level framework is used extensively in the transportation planning literature to address problems such as the network design problem and facility location problem (Miralinaghi et al. 2020b; a; Seilabi et al. 2020). In this problem, in the upper-level, the transportation decision makers (agency and the private sectors) seek to minimize the total system travel time of the travelers and to maximize the parking fee revenues and the benefits of decommissioning existing parking facilities (Labi 2014; Sinha and Labi 2007). They intend to do this making optimal decisions regarding the location, timing, and capacity of any new parking facilities, the timing of the decommissioning of existing ones, and optimal design of differentiated parking fees for AVs and HDVs at each parking facility in each period of the analysis horizon. Based on these decisions at the upper-level, the travelers (in the lower-level) make decisions regarding their route and parking choices in each period. Each traveler seeks to minimize their total travel cost, which has different components for AV and HDV travelers and is also based on the traveler's parking needs (Table 2). For AV travelers that require parking in one of the available public parking facilities (PPF), this cost includes the in-vehicle travel time, AV-specified parking fee, and the additional operating cost of vehicle relocation from each traveler's destination to their intended parking facility. For HDV travelers who need to park at similar locations, this cost includes the in-vehicle travel time, HDV-specified parking fee, and the last-mile travel time. The last-mile travel time is referred to as the travel time of the HDV travelers after parking their vehicles which can include walking and transit time. It is clear that AV travelers do not bear this cost because we assume that they will be dropped off at their destination. Further, the travel cost of AV and HDV travelers who have parking available in their destinations consists of only the in-vehicle travel cost.

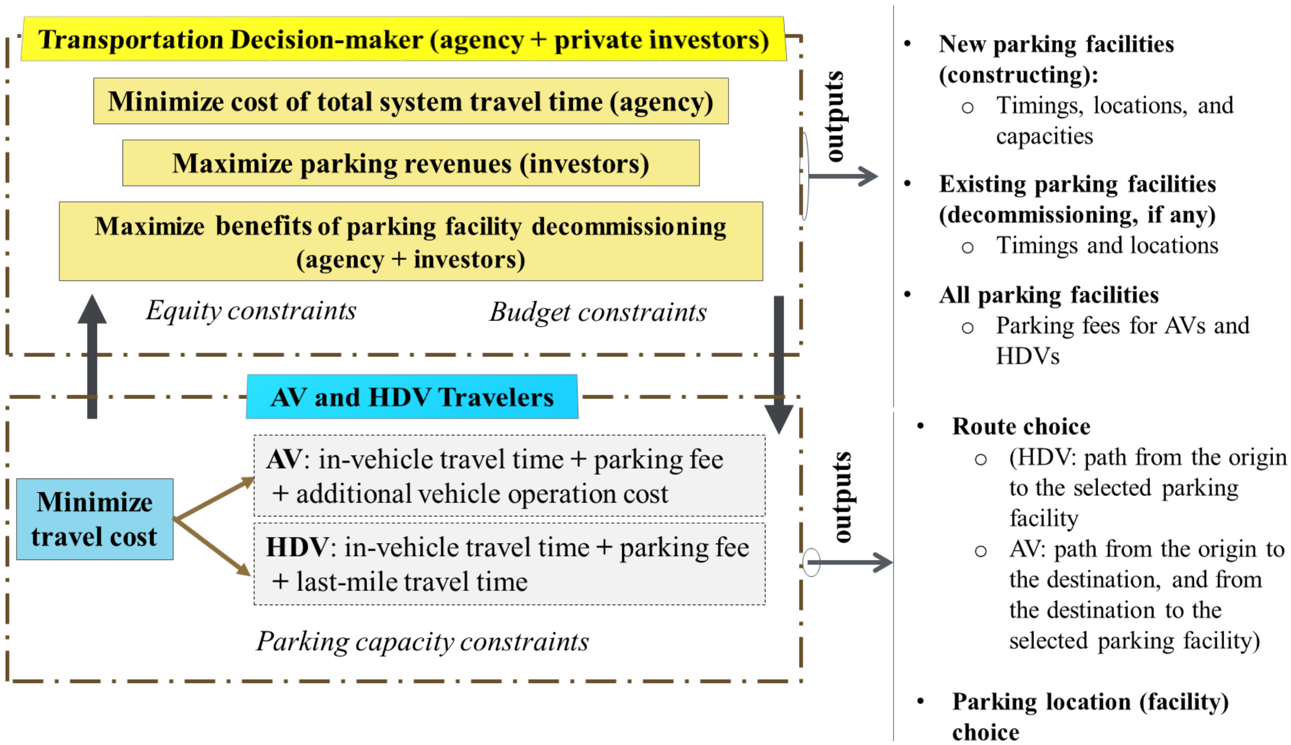


Figure 2. The bi-level structure of the problem

Table 2. Different cost components for AV and HDV travelers

Parking needs	AV/HDV	In-vehicle travel time cost	Last mile travel time cost	Parking fee	Additional operating cost
Travelers wishing to park at PPF	AV	✓	×	✓	✓
	HDV	✓	✓	✓	×
Travelers that do not wish to park at PPF	AV	✓	×	×	×
	HDV	✓	×	×	×

3.2 Preliminaries

Let $G = (N, A)$ represent the transportation network where N and A denote the set of nodes and links, respectively. Let T, M, and $\widetilde{G}$ denote the set of periods ($t \in T$), user groups ($m = 1, 2$ for HDV and AV travelers, respectively), and user sub-groups ($\widetilde{g} = 1, 2$ for parking required travelers and no parking required travelers, respectively), respectively. Each period (t) corresponds to a period with a duration of few years. Let K represent the set of candidate parking facility nodes, and K' represent the set of existing parking facility nodes. Further, R, S, and W denote the set of origins, destinations, and origin-destinations with indices r, s, and w, respectively. Sets R, S, K, and K' are all subsets of N. Let $\sigma_{i,j}^{t}$ and $v_{i,j}^{t}$ denote the travel time and traffic flow of link (i, j) in period t, respectively. These two variables represent the average travel time and traffic flow of link (i, j) in the entire duration of period t. The travel time of link (i, j) follows the Bureau of Public Roads (BPR) function which can be expressed as:

$$\sigma_{i,j}^{t}(v_{i,j}^{t}) = \sigma_{0,i,j}^{t}\left(1 + 0.15\left(\frac{v_{i,j}^{t}}{\chi_{i,j}^{t}}\right)^{4}\right) \qquad \forall (i, j) \in A - A^{D}, \forall t \qquad (1)$$

where $\sigma_{0,i,j}^{t}$ and χ_{ij}^{t} denote the free-flow travel time and capacity of the link (i, j) in period t, respectively. A^{D} is also the set of dummy links which is a subset of A.

3.3 Assumptions

In the analysis, a number of assumptions were made. First, it is assumed that the travelers considered, regardless of their user group (HDV vs. AV) are daily commuters who need to park their vehicles at one of the available parking facilities in the network (that is, group $\widetilde{g} = 1$ travelers), or daily commuters that have a parking space available at their destination, (that is, group $\widetilde{g} = 2$ travelers). Let $q_{r,s,m}^{t,\widetilde{g}}$ denote the given travel demand of sub-group $\widetilde{g}$, and user group m travelers of origin-destination (r, s) in period t. Second, this study considers that there is not parking need of AV travelers that send their vehicles back to their origins to be parked there or be used by their other family members for other day-to-day purposes. Further, we assume that AVs are all private and personal. In other words, this study does not consider shared AVs. This assumption is very important because shared AVs are used for more trips and their parking needs are also different as well.

Third, this study assumes that the combined parking capacity of all parking facilities in each period satisfies the total parking demand in that period. Without assuming so, not all of the trips can be completed which is not acceptable. This assumption can be considered realistic because, typically, there exist abundant and relatively inexpensive parking spots outside of downtown areas. These parking locations may not be preferable for HDV travelers because, by parking at these locations, they bear a significantly high cost of last-mile travel time. However, AV travelers may find such parking locations favorable as they avoid the last-mile travel time by being dropped off at their destinations. The AV's need to consider the additional vehicle operating cost of the extra travel made by their vehicle from the drop-off/pick up points to such parking locations that are located far away.

Fourth, this study assumes that for each parking facility, the parking fee incurred by the travelers of each user group is constant during each period. Besides, the transportation decision maker considers different price levels for this differentiated parking fee. More specifically, let Ψ^t be the level 1 parking fee in period t in dollars. To establish the actual fee that each traveler pays in each period for patronizing a specific parking facility, this parameter is multiplied by $H_{k,m}^t$. $H_{k,m}^t$ is an integer variable representing the fee level of parking facility k for user group m travelers in period t. We also denote the maximum fee level of each parking facility by ϱ. In other words, $H_{k,m}^t$ is equal to 0 for an unavailable parking facility, 1 for a parking facility with a level 1 fee, and ϱ for a parking facility with a level ϱ fee. The Figure 3 illustrates how the parking facility fee leveling works.

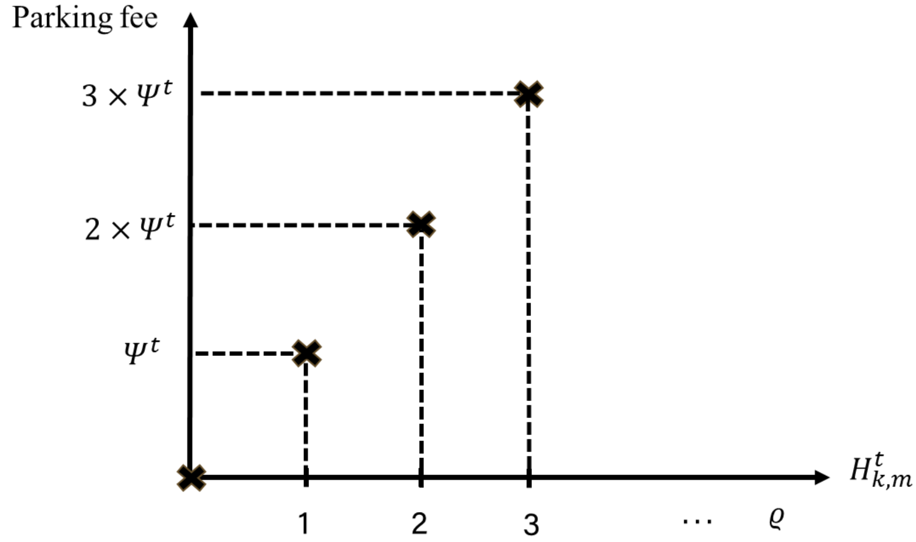


Figure 3. Parking facility fee leveling

Fifth, it is assumed that the transportation decision-maker considers different capacity levels for a parking facility construction. Let f_k^t and γ_k^t denote the given construction cost and parking capacity level 1 for facility k in period t, respectively. Q_k^t is an integer variable representing the capacity level of the parking facility k in period t. This, for example, $=1$ for level 1, $=2$ for level 2, and so on. We denote the maximum level of parking capacity by ς. Hence, $Q_k^t = \varsigma$ for a level ς parking facility. Hence, the capacity and construction cost of level Q_k^t parking facility k in period t are $Q_k^t \cdot \gamma_k^t$ and $f_k^t \cdot \vartheta(Q_k^t, \delta_k^t)$, respectively. $\vartheta(Q_k^t, \delta_k^t)$ is assumed to be a linear function of Q_k^t and δ_k^t which incorporates the parking facility capacity level and availability by considering the economy of scale to derive the construction cost level of a level Q_k^t parking facility and is as follows:

$$\vartheta\,(Q_k^t, \delta_k^t) = \delta_k^t + \iota_1 \cdot Q_k^t \qquad \forall k \in K, \forall t \tag{2}$$

Where: $\iota_1 < 1$ is a parameter that incorporates the economy of scale in obtaining the construction cost level of a level Q_k^t parking facility. In this function, the first part (δ_k^t) accounts for the initial construction cost and the second part ($\iota_1 \cdot Q_k^t$) accounts for the construction variable cost which is a function of the parking facility capacity. Figure 4 illustrates the assumed relationship between parking facility capacity and construction cost.

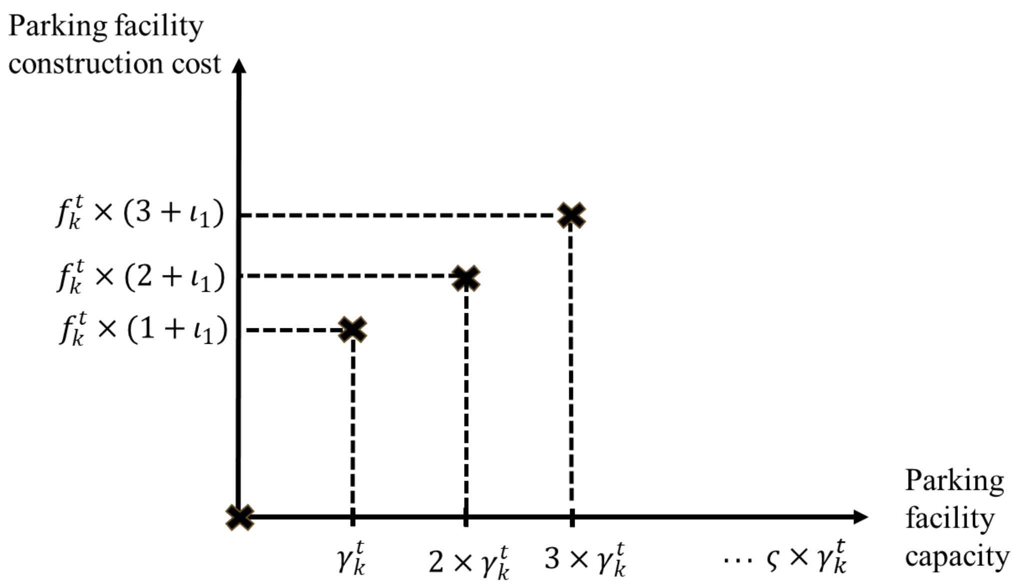


Figure 4. Parking facility capacity vs. construction cost

Finally, we assume that after a parking facility is constructed in one of the periods with a certain capacity, that capacity will be available in that period and subsequent periods. This capacity cannot be changed once the parking facility has been constructed. Further, once an existing parking facility is decommissioned in a specific period, the travelers cannot utilize it for parking purposes in that period, and subsequent periods. In other words, the availability condition of each parking facility can be changed only once in the entire planning horizon.

3.4 Upper-level model

In the upper-level, the transportation decision maker seeks to minimize the weighted sum of the total system travel cost of the travelers (Π_1), maximize the total parking revenues (Π_2), and maximize the monetary benefits of decommissioning a number of existing parking facilities (Π_3). The weights ξ_1 to ξ_3 are associated with the upper-level objective function components Π_1 to Π_3, respectively. Figure 5 summarizes the costs and revenues that are considered in the upper-level by the transportation decision makers in an input-outcomes diagram. The transportation decision maker establishes (i) the location and capacity of new parking facilities, (ii) whether to decommission some of the existing parking facilities and (iii) the differentiated (HDV and AV) parking fee in each period of the analysis horizon. δ_k^t denotes a binary variable which is equal to 1 if the facility k is available for parking in period t, and 0 otherwise. Further, φ^t denotes the maximum acceptable HDV-AV travel cost ratio (HATCOR) in period t and υ^t denotes the maximum HDV travel cost ratio (HTCOR) in period t. The travel cost of the user sub-group $\overset{\frown}{g}$ of group m travelers for origin-destination (O-D) pair (r, s) in period t is denoted by $u_{r,s,m}^{t,\overset{\frown}{g}}$. Further, $x_{i,j}^t$ and $y_{i,j}^t$ present the traffic flow of HDV and AV travelers in the link (i, j) in period t, respectively. Besides, Ψ_k^t represents the parking facility k revenues in period t due to fees collected from both HDV and AV travelers. Let ω_k^t denote the monetary gain of decommissioning the existing facility k in period t, and $\overline{\omega}_k^t$ denote the decommissioning cost of existing parking facility k in period t. Finally, $\bar{Q}^{k'}$ is the given capacity level of the existing parking facility at node k'.

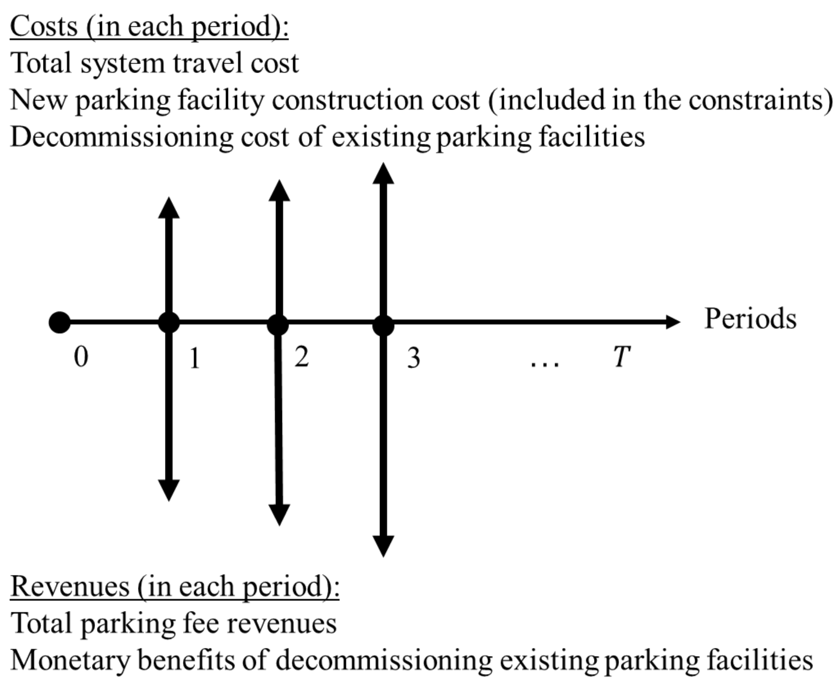


Figure 5. A sample input-outcomes diagram for the transportation decision makers

Based on this set of notations, the upper-level model can be formulated as the following mixed-integer nonlinear problem (MINLP):

$$\text{Min } Z^U = \xi_1 \cdot \Pi_1 - \xi_2 \cdot \Pi_2 - \xi_3 \cdot \Pi_3 \tag{3}$$

$$\Pi_1 = \sum_{t \in T} \sum_{(i,j) \in A} \Delta^t \cdot \theta_t^1 \cdot \sigma_{i,j}^t \cdot x_{i,j}^t + \sum_{t \in T} \sum_{s \in S} \sum_{k \in K} \Delta^t \cdot \theta_t^1 \cdot x_{k,d_2^s}^{s,t,1} \cdot \bar{g} \cdot g_k^{s,t} + \sum_{t \in T} \sum_{(i,j) \in A} \Delta^t \cdot \theta_t^2 \cdot \sigma_{i,j}^t \cdot y_{i,j}^t \tag{4}$$

$$\Pi_2 = \sum_{t \in T} \sum_{k \in K} \Gamma_k^t \tag{5}$$

$$\Pi_3 = \sum_{t \in T} \sum_{k \in K'} (\omega_k^t \cdot (1 - \delta_k^t) - \overline{\omega}_k^t \cdot (\delta_k^t - \delta_k^{t-1})) \tag{6}$$

$$\frac{u_{r,s,2}^{t,1}}{u_{r,s,1}^{t,1}} \geq \varphi^t \qquad \forall (r,s), \forall t \tag{7}$$

$$\frac{u_{r,s,1}^{t,1,pre}}{u_{r,s,1}^{t,1}} \geq \upsilon^t \qquad \forall (r,s), \forall t \tag{8}$$

$$\sum_{k \in K} f_k^t \cdot (\vartheta(Q_k^t, \delta_k^t) - \vartheta(Q_k^{t-1}, \delta_k^{t-1})) \leq B^t \qquad \forall t \tag{9}$$

$$\delta_k^{t+1} \geq \delta_k^t \qquad \forall k \in K, \forall t \tag{10}$$

$$\delta_k^t \leq Q_k^t \leq \varrho \cdot \delta_k^t \qquad \forall k \in K, \forall t \tag{11}$$

$$\delta_k^{t+1} - \delta_k^t \leq Q_k^{t+1} - Q_k^t \leq \varsigma \cdot (\delta_k^{t+1} - \delta_k^t) \qquad \forall k \in K, \forall t \tag{12}$$

$$\delta_{k'}^{1} = 1 \qquad \forall k' \in K', \forall t \tag{13}$$

$$\delta_{k}^{t+1} \leq \delta_{k}^{t} \qquad \forall k \in K', \forall t \tag{14}$$

$$Q_{k'}^{t} = \bar{Q}^{k'} \cdot \delta_{k'}^{t} \qquad \forall k \in K', \forall t \tag{15}$$

$$\sum_{k \in K \cup K'} \gamma_k^t \cdot Q_k^t \geq \sum_{m} \sum_{(r,s) \in W} q_{r,s,m}^{t,1} \qquad \forall t \tag{16}$$

$$\delta_{k}^{t} \leq H_{k,m}^{t} \leq \varrho \cdot \delta_{k}^{t} \qquad \forall m, \forall k, \forall t \tag{17}$$

$$x \in x^{UE}, y \in y^{UE}, v \in v^{UE}, u \in u^{UE} \tag{18}$$

$$\delta_k^t \in \{0,1\},\ Q_k^t \in \{0,1, \dots, \varsigma\},\ H_{k,m}^t \in \{0,1, \dots, \varrho\} \qquad \forall k, \forall t \tag{19}$$

where θ_m^t is the value of time for user group $m$travelers in period t (\$/hr), B^t is the construction budget in period t, and Δ^t transforms the cost in period t to present value and also considers the period duration. The objective function (3)-(6) minimizes the weighted total in-vehicle travel cost of all travelers and total last-mile travel cost of HDV travelers, and maximizes the total parking fee revenues and monetary benefits of decommissioning a number of existing parking facilities. Constraint (7) is the HATCOR equity constraint which ensures that the travel cost of sub-group 1 HDV travelers is not significantly higher than that of AV travelers for each OD pair in each period, by a specified margin. Constraint (8) is the HTCOR equity constraint which ensures that the travel cost of sub-group 1 HDV travelers in each period does not increase significantly compared to their former travel cost which is denoted by $u_{r,s,1}^{t,1,pre}$.

Constraints (9)-(12) are associated with the construction of new parking facilities. Constraint (9) ensures that the budget constraint for constructing new parking facilities in each period t is met. More specifically, if a parking facility k with capacity level Q is constructed in period t', $\delta_{k}^{t} = 1$, and $Q_{k}^{t} = Q$ for $\forall t \geq t'$. Further, the term $f_{k}^{t} \cdot (\vartheta(Q_{k}^{t}, \delta_{k}^{t}) - \vartheta(Q_{k}^{t-1}, \delta_{k}^{t-1}))$ in constraint (9) will be equal to $f_{k}^{t} \cdot \vartheta(Q, 1)$ that is equal to the construction cost of a level Q parking facility k in period t. Constraint (10) guarantees that if a parking facility is constructed in a period, it must remain available for parking in the next periods. Constraint (11) defines the bounds of each parking facility capacity level with regards to that parking facility availability in each period. More specifically, Q_{k}^{t} can only be positive if $\delta_{k}^{t} = 1$. Besides, Q_{k}^{t} needs to be less than or equal to ϱ if $\delta_{k}^{t} = 1$ which is the maximum level of parking capacity. Constraint (12) maintains that after a parking facility is constructed with a specific capacity level, its capacity must remain unchanged in the next period.

Constraints (13)-(15) are associated with the existing parking facilities and their possible decommissioning. Constraint (13) specifies that the existing parking facilities are available for parking in period 1, while constraint (14) states that an currently available existing parking facility available during a certain period, might not be available in the next period. It also states that after a parking facility is decommissioned, it cannot be utilized for parking for the rest of the planning horizon. Constraint (15) maintains that the capacity level of the parking facility k' is equal to its given initial capacity ($\bar{Q}^{k'}$) if it is still available for parking in period t. Constraint (16) ensures that the total parking supply in each period meets the total parking demand of both HDV and AV user groups.

Constraint (17) states that the parking fee level for AV or HDV at each parking facility is positive if that parking facility is available for parking in that period. Further, the fee level cannot be greater than the maximum fee level, ϱ. Last but not least, constraint (18) states that the link travel times and total travel cost of each origin-destination, user group, and sub-group are established by the lower-level model. Finally, constraint (19) specifies the binary and integer domain of the upper-level decision variables.

3.5 Lower-level model

In the lower level, travelers minimize their travel costs. For each traveler, the travel cost depends on the selected route and any available parking facility. Figure 6 presents the travel and parking behavior of sub-group 1 AV and HDV travelers. The sub-group 1 HDV travelers' travel cost consists of the travel time from the origin to the parking facility, the last-mile travel time (i.e., walking time after parking the vehicle), and the parking fee. The sub-group 2 HDV travelers only consider the travel time from their origins to their destinations, because they have parking spots available at their destinations. The travel cost of each sub-group 1 AV traveler includes travel time from the origin to the destination, operation fees, and the parking fee. Similar to the HDV travelers, the sub-group 2 AV travelers only consider the travel time from their origins to their destinations, since they also have parking available at their destinations. The travel and parking behavior of the HDV and AV travelers can be expressed through separate complementarity equilibrium constraints. These equilibrium constraints ensure that all travelers of a same group and sub-group for a specific OD have equal travel costs in each period of the analysis horizon. Further, they cannot improve their travel costs by unilaterally changing their decisions. These constraints, along with the parking capacity and link travel time aggregation constraints, constitute the lower-level model. Hence, the constraints in the lower-level model has three parts. These parts are presented, and then the lower-level model is reformulated as a decomposable convex program so that it can be solved more efficiently.

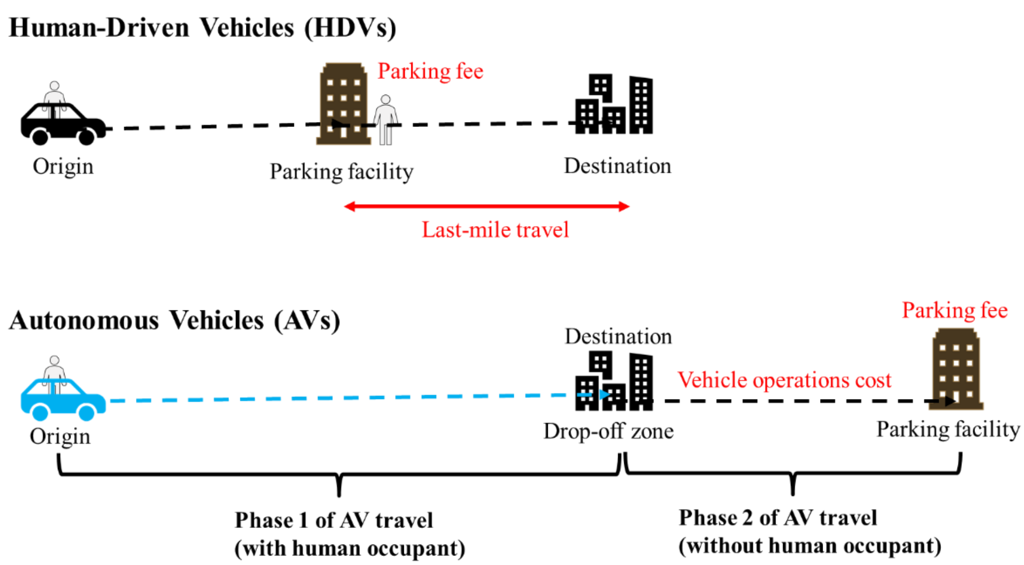


Figure 6. Travel and parking behavior modeling of sub-group 1 of AVs and HDV travelers

3.5.1 Part 1 (Both AV and HDV travelers)

There exist a number of constraints in the lower-level model that are mutual to AVs and HDVs and model the traffic network attributes which are the parking capacity, link flows aggregation, and the parking revenue constraints. These constraints are presented below and subsequently explained.

$$\sum_{s\in S} x_{k,d_1^s,1}^{s,t} + \frac{1}{\aleph} \cdot \sum_{s\in S} y_{k,d_2^s,1}^{d_2^s,t,2} \leq Q_{k}^{t} \cdot \gamma_k^t \qquad \forall k, \forall t \tag{20}$$

$$0 \leq \rho_k^t \perp \left(-\sum_{s\in S} x_{k,d_m^s,1}^{s,t} - \frac{1}{\aleph} \cdot \sum_{s\in S} y_{k,d_2^s,1}^{d_2^s,t,2} + Q_{k}^{t} \cdot \gamma_k^t \right) \geq 0 \qquad \forall k, \forall t \tag{21}$$

$$v_{i,j}^t = \sum_{\hat{g}} \sum_{s\in S} x_{i,j,g}^{s,t} + \sum_{\hat{g}} \sum_{s\in S} y_{i,j,\hat{g}}^{s,t,1} + \sum_{s\in S} y_{i,j,2}^{d_2^s,t,2} \qquad \forall (i,j) \in A, \forall t \tag{22}$$

$$\Gamma_k^t = \sum_{s\in S} x_{k,d_m^s,1}^{s,t} \cdot \overline{\Psi}^t H_{k,1}^t + \sum_{s\in S} y_{k,d_2^s,1}^{d_2^s,t,2} \cdot \overline{\Psi}^t H_{k,2}^t \qquad \forall k, \forall t \tag{23}$$

$$\rho_k^t \geq 0 \qquad \forall k, \forall t \tag{24}$$

Constraint (20) is the parking facility capacity constraint which maintains that in each period of the analysis horizon, the total number of vehicles parked at the parking facility k cannot exceed the parking capacity. This constraint also considers the fact that AVs require less parking space compared to HDVs by dividing the rate of parked AVs by the parameter $\aleph$ ($\aleph > 1$). It should be noted that if parking facility k is not available for parking in period t, then Q_{k}^{t} is equal to zero, meaning that no vehicle uses that parking facility. The complementarity constraint (21) ensures that the travelers experience the extra cost ρ_k^t only if the parking facility capacity is met or if it is not available for parking. This extra cost can be interpreted as the time delay travelers may experience because of the non-availability of parking at their desired or intended parking location.

Last but not least, constraint (22) specifies the total aggregate flow for each link. Besides, constraint (23) specifies the total parking revenues for each parking facility in each period. Finally, constraint (24) guarantees the non-negativity of continuous cost variable ρ_k^t.

3.5.2 Part 2 (AV travel modeling)

An AV traveler may choose to drive directly to their destination, and then dispatch their vehicle to their desired parking facilities. We refer to the first part of their trips as phase 1 of AV travel (see Figure 6). In this phase, the AV travelers are physically in the vehicle and incur in-vehicle travel time. This phase is experienced by each of the two sub-groups of AV travelers regardless of their parking requirements. As the sub-group 1 AV travelers leave their vehicles in the designated drop-off zones and head to their destinations, their vehicles start another trip without them, and drive to their desired parking facilities which we refer this trip as phase 2 of AV travel. In phase 2, the AV travelers are not physically in the vehicle. Therefore, they incur only a parking fee and also the vehicle operations cost of their trip from the drop-off locations to the parking facility.

In phase 1, both sub-groups of AV travelers start their trips at their corresponding origins, end it at their destinations, and seek to minimize their total travel times. In phase 2, the AVs incur not only a vehicle operation cost that is assumed to be proportional to the travel time of their trips, but also need to consider the parking fee they need to pay. In other words, phase 2 of AV travel is a combined route and parking selection process. In this dissertation, we define a set of dummy nodes and links and add to the network which helps us model this phase. A dummy node (d_2^s) is defined for each destination s, which represents that destination for AVs in phase 2 of their travel. Further, each parking facility node (k) is connected to each of the dummy nodes via dummy links (k, d_2^s). The cost of these dummy links account for the AV-specified parking fee for parking in that location and is as follows:

$$\sigma_{k,d_2^s}^t = \Psi^t \cdot H_{k,2}^t \qquad \forall k, \forall s, \forall t \qquad (25)$$

Figure 7 illustrates this network transformation for one destination and K parking facilities. As the AVs are parked at one of the parking facilities $k = 1$, $k = 2$, …, or $k = K$, they need to traverse through one of the dummy links ($k = 1, d_2^s$), ($k = 2, d_2^s$), …, or ($k = K, d_2^s$) to finish their trips. It should be noted that the links drawn from node s toward the parking facility nodes can be each a path with multiple links. The purpose of this illustration is to demonstrate that the trip in phase 2 is started at node s.

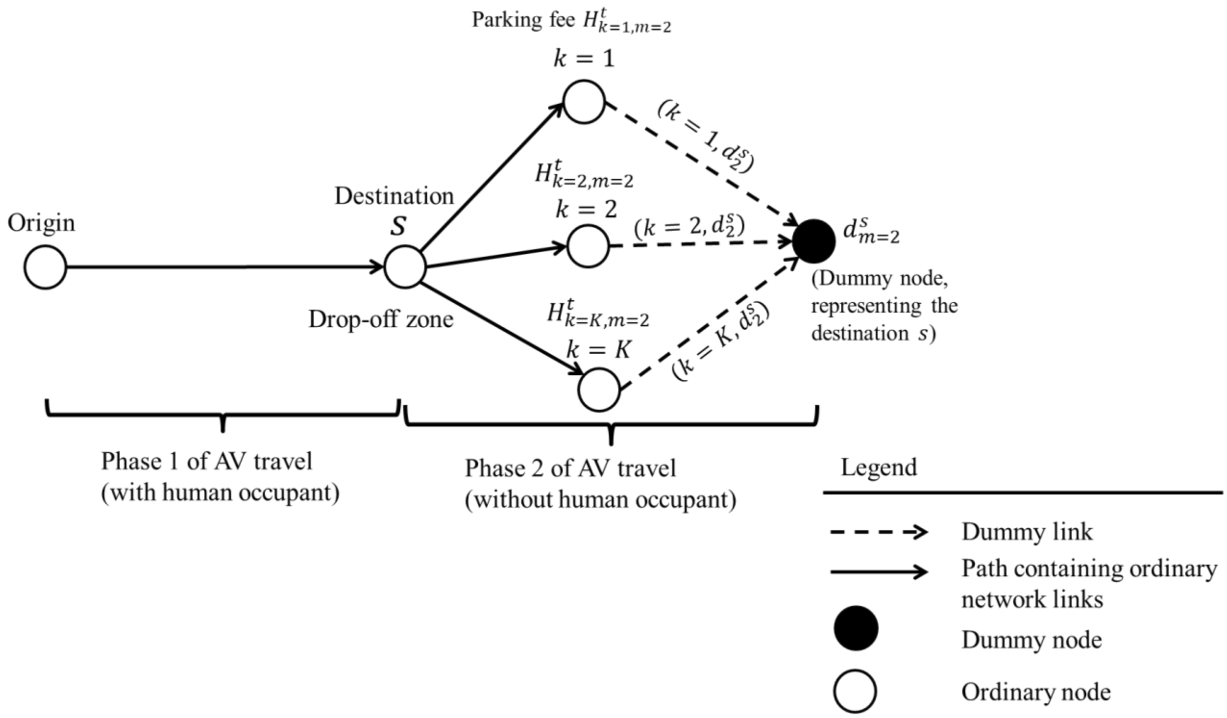


Figure 7. Network transformation for phase 2 of the AV travel

Let $y^{s,t,1}_{i,j,\tilde{g}}$ illustrate the traffic flow of user sub-group $\tilde{g}$ AV travelers traversing link (i,j) in period t that have destination s in phase 1. Further, to model phase 2 of the travel, $y^{d_2^s,t,2}_{i,j,1}$ denotes the traffic flow of AVs traversing the link (i,j) in phase 2 in period t that have already dropped off their travelers at destination s. Further, $\lambda^{s,t,1}_{i,\tilde{g}}$ denotes the travel time from node i to destination s for a sub-group $\tilde{g}$ AV traveler in period t. Similarly, $\lambda^{d_2^s,t,2}_{i,1}$ denotes the travel time from node i to the dummy node d_2^s for AVs that have already dropped off their travelers at destination s in period t. The following constraints ((26)-(38)) are imposed on the combined travel and parking behavior of the AV travelers.

$$0 \le y^{s,t,1}_{i,j,\tilde{g}} \perp \left(\sigma^t_{i,j}\left(v^t_{i,j}\right) - \lambda^{s,t,1}_{i,\tilde{g}} + \lambda^{s,t,1}_{j,\tilde{g}}\right) \ge 0 \qquad \forall(i,j) \in (A - A^D), \forall \tilde{g}, \forall s, \forall t \tag{26}$$

$$0 \le y^{d_2^s,t,2}_{i,j,1} \perp \left(\sigma^t_{i,j}\left(v^t_{i,j}\right) - \lambda^{d_2^s,t,2}_{i,1} + \lambda^{d_2^s,t,2}_{j,1}\right) \ge 0 \qquad \forall (i,j) \in (A - A^D), \forall s, \forall t \tag{27}$$

$$\lambda^{s,t,1}_{s,\overbrace{g}} = 0 \qquad \forall \overbrace{g}, \forall s, \forall t \tag{28}$$

$$\lambda^{d_2^s,t,2}_{d_2^s,1} = 0 \qquad \forall s, \forall t \tag{29}$$

$$0 \le y^{d_2^s,t,2}_{k,d_2^s,1} \perp \left(\bar{\theta}\frac{1}{\theta}\bar{\Psi}^t H^t_{k,2} - \lambda^{d_2^s,t,2}_{k,1} + \lambda^{d_2^s,t,2}_{d_2^s,1} + \frac{1}{\aleph}\cdot\rho^t_k\right) \ge 0 \qquad \forall (k, d_2^s) \in A^D, \forall t \tag{30}$$

$$\sum_{j:(j,i)\in A} y^{s,t,1}_{j,i,\overbrace{g}} - \sum_{j:(i,j)\in A} y^{s,t,1}_{i,j,\overbrace{g}} = \bar{b}^{s,t}_{i,\overbrace{g}} \qquad \forall i, \forall s, \forall \overbrace{g}, \forall t \tag{31}$$

$$\sum_{j:(j,i)\in A} y^{d_2^s,t,2}_{j,i,2} - \sum_{j:(i,j)\in A} y^{d_2^s,t,2}_{i,j,2} = \bar{\bar{b}}^{d_2^s,t}_{i} \qquad \forall i, \forall s, \forall t \tag{32}$$

$$y^t_{i,j} = \sum_{s\in S}\sum_{\overbrace{g}} y^{s,t,1}_{i,j,\overbrace{g}} \qquad \forall (i,j) \in (A - A^D), \forall t \tag{33}$$

$$u^t_{r,s,2} = \lambda^{s,t,1}_{r,1} + \frac{1}{\bar{\theta}}\lambda^{d_2^s,t,2}_{s,1} \qquad \forall r, \forall s, \forall t \tag{34}$$

$$y^{s,t,1}_{i,j,g} \ge 0 \qquad \forall (i,j) \in A, \forall g, \forall s, \forall t \tag{35}$$

$$y^{d_2^s,t,2}_{i,j,1} \ge 0 \qquad \forall (i,j) \in A, \forall s, \forall t \tag{36}$$

$$\lambda^{s,t,1}_{i,g} \ge 0 \qquad \forall i, \forall s, \forall g, \forall t \tag{37}$$

$$\lambda^{d_2^s,t,2}_{i,1} \ge 0 \qquad \forall i, \forall s, \forall t \tag{38}$$

where $\bar{b}^{s,t}_{i,\overbrace{g}}$ and $\bar{\bar{b}}^{d_2^s,t}_{i,2}$ in equations (31) and (32) are defined in equations (39) and (40), respectively, as follows:

$$\bar{b}_{i,\widehat{g}}^{s,t} = \begin{cases} -q_{i,s,2}^{t,\widehat{g}} & \text{if } i \in R \\ 0 & \text{if } i \notin R, \text{ and } i \neq s \\ \sum_{r \in R} q_{r,s,2}^{t,\widehat{g}} & \text{if } i = s \end{cases} \qquad \forall i, \forall s, \forall t, \forall \widehat{g} \tag{39}$$

$$\bar{\bar{b}}_{i,2}^{d_2^s,t} = \begin{cases} -\sum_{r \in R} q_{r,s,2}^{t,1} & \text{if } i = s \\ 0 & \text{if } i \neq s \text{ and } i \neq d_2^s \\ \sum_{r \in R} q_{r,s,2}^{t,1} & \text{if } i = d_2^s \end{cases} \qquad \forall i, \forall s, \forall t \tag{40}$$

The complementarity constraint (26), the destination- and link-based user equilibrium condition for phase 1, ensures that if sub-group $\widehat{g}$ AV travelers with destination s traverse through link (i, j) in period t, then that link is part of the shortest-path route for that destination. Constraint (27) is similar to constraint (26) but is exclusively for sub-group 1 AV travelers at phase 2 of their trips. Constraint (28) states that the travel time from each destination node s to itself is zero for both sub-groups of AV travelers in phase 1. Similarly, constraint (29) indicates that the travel time from the dummy node d_2^s to itself is zero for sub-group 1 AV travelers in phase 2. Constraint (30) is also similar to complementarity constraints (26) and (27) but refers only to dummy links in the second trip phase of sub-group 1 AVs, and includes an additional term (ρ_k^t). This constraint maintains that if link (k, d_2^s) is not part of a feasible route for the AVs, then there is an additional perceived cost (ρ_k^t) that discourages the AVs from using that dummy link. In this constraint, $\bar{\theta}$ is the relative value of travel cost compared to vehicle operations cost for AV travelers, and is multiplied by the parking fee (dummy link's cost) to obtain the actual time value of the vehicle operations. This accounts for the different value of the travel cost operation cost ratio in phase 2 of AV travel. Constraints (31) and (39) are the flow conservation constraints for AV travel in phase

1 for both sub-groups. Similarly, constraints (32), and (40) represent phase 2 of travel for sub-group 1 AVs. Last but not least, constraint (33) aggregates the traffic flow of AV travelers in phase 1 for each destination and user sub-group to obtain the total traffic flow of AV travelers in each link. It should be noted that $y_{i,j}^{t}$ accounts for only the AV travelers in phase 1 of their travel that use the link (i, j). Constraint (34) computes the travel cost of sub-group 1 AV travelers for OD pair (r, s) in period t. Finally, constraints (35)-(38) illustrate the non-negativity of the decision variables regarding for AV travel at the lower level of the framework.

3.5.3 Part 3 (HDV travel modeling)

As stated earlier, HDV travelers are divided into two sub-groups based on their parking requirements. Sub-group 1 HDV travelers need to park their vehicles at one of the available parking facilities while sub-group 2 have parking spots provided at their destinations. Each of the two sub-groups intends to minimize their in-vehicle travel time from their origin to their destination. In addition, sub-group 1 travelers need to consider additional criteria: parking fee and the "last-mile travel" time. After selecting a parking facility and parking their vehicles, HDV travelers can travel the last mile of their trips by walking, taking a shuttle, and so on. In this study, this is referred to as the "last mile travel". Taking into consideration that the network links represent roads for driving purposes, they cannot be used to model the last part of these HDV travelers' trips. To overcome this dilemma, dummy nodes and links are added to the network, similar to that described in Section 3.5.2 for AV travel. We define a dummy node (d_1^s) for each destination s which represents that specific destination for sub-group 1 HDV travelers. Then, we connect each of the network parking facility nodes to each of these dummy nodes via dummy links. Figure 8 illustrates this network transformation for K parking facilities and 1 destination in which one dummy node and K dummy links are added to the network. In this figure, the sub-group 1 HDV travelers with destination s need to patronize one of the dummy links $(k = 1, d_1^s)$, $(k = 2, d_1^s)$… or $(k = K, d_1^s)$ in order to park their vehicles and reach their destination. It is also needed to account for the relative walking discomfort compared to driving which is defined as $\bar{g}$ in this study, and maintains that $\bar{g}$-minute walk (last-mile travel) has a similar disutility as 1-minute drive for the travelers. $\bar{g}$ can be a function of the attributes of the travelers (age, health, etc.) and the environment (weather conditions, walkway accessibility, and traffic and pedestrian traffic (Chen et al. 2020; Hoogendoorn 2004; Sánchez-Martínez 2017)). Against this background, the travel cost of link (k, d_1^s) in period t reflects the parking facility k fee for HDVs in period t (i.e., $\bar{\Psi}^t \cdot H_{k,1}^t$), and also the transformed cost value of last-mile travel time between parking facility k and destination s in period t (i.e., $\theta_1^t \cdot \bar{g} \cdot g_k^{s,t}$). The last-mile travel time is multiplied by the HDV travelers' value of time in period t (θ_1^t) and also the relative walking discomfort factor compared to driving ($\bar{g}$). Hence, it can formulated as follows:

$$\sigma_{k,d_1^s}^t = \bar{\Psi}^t \cdot H_{k,1}^t + \theta_1^t \cdot \bar{g} \cdot g_k^{s,t} \qquad \forall k, \forall s, \forall t \qquad (41)$$

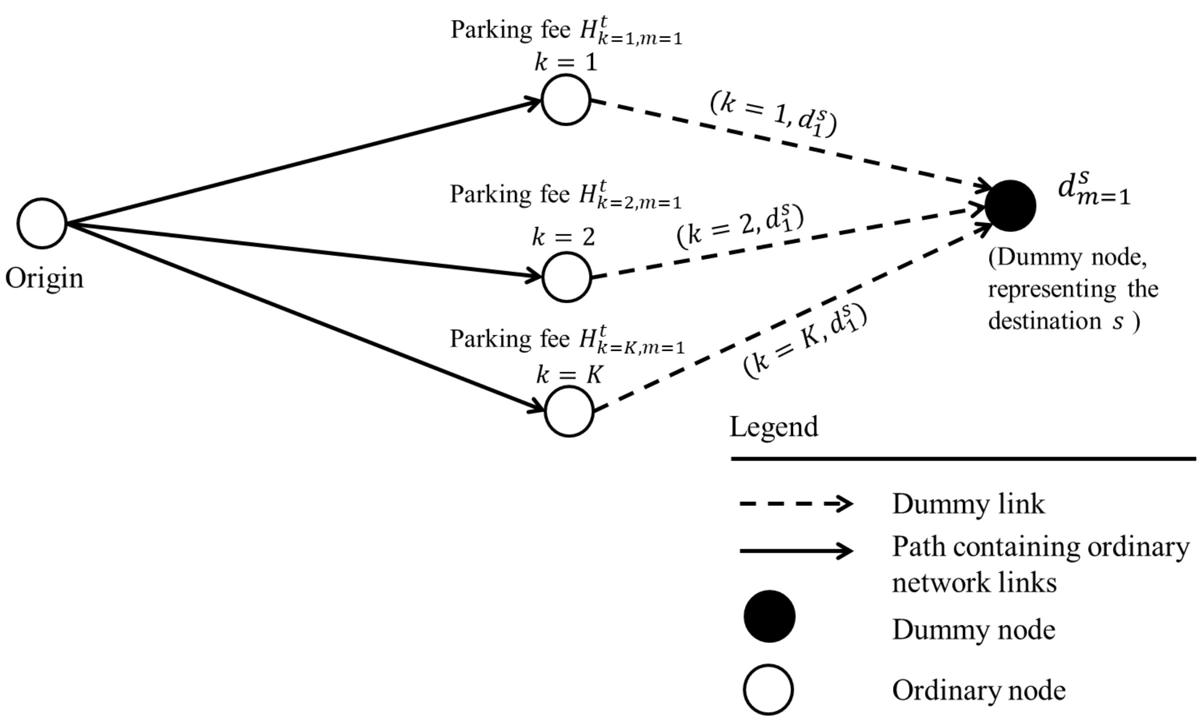


Figure 8. Network transformation for the last mile travel of sub-group 1 HDV travelers

Let $x_{i,j,\tilde{g}}^{s,t}$ denote the traffic flow of sub-group $\tilde{g}$ HDV travelers traversing through link (i, j) with destination s in period t. Besides, $\pi_{i,g}^{s,t}$ illustrates the travel time from network node i to destination s for sub-group $\tilde{g}$ HDV travelers in period t. On this basis, the combined travel and parking behavior of the HDV travelers can be modeled using the following constraints:

$$0 \le x_{i,j,\widetilde{g}}^{s,t} \perp \left(\sigma_{i,j}^t\left(v_{i,j}^t\right) - \pi_{i,\widetilde{g}}^{s,t} + \pi_{j,\widetilde{g}}^{s,t}\right) \ge 0 \qquad \forall (i,j) \in (A - A^D), \forall \widetilde{g}, \forall s, \forall t \qquad (42)$$

$$\pi_{s,2}^{s,t} = 0 \qquad \forall s, \forall t \qquad (43)$$

$$\pi_{d_1^s,1}^{s,t} = 0 \qquad \forall s, \forall t \qquad (44)$$

$$0 \le x_{k,d_1^s,1}^{s,t} \perp \left(\frac{1}{\theta_1^t}\bar{\Psi}^t H_{k,1}^t + \bar{g} \cdot g_k^{s,t} - \pi_{k,1}^{s,t} + \pi_{d_1^s,1}^{s,t} + \rho_k^t\right) \ge 0 \qquad \forall (k, d_1^s) \in A^D, \forall t \qquad (45)$$

$$\sum_{j:(j,i)\in A} x_{j,i,\widetilde{g}}^{s,t} - \sum_{j:(i,j)\in A} x_{i,j,\widetilde{g}}^{s,t} = b_{i,\widetilde{g}}^{s,t} \qquad \forall i, \forall s, \forall \widetilde{g}, \forall t \qquad (46)$$

$$x_{i,j}^t = \sum_{s\in S} \sum_{\widetilde{g}} x_{i,j,\widetilde{g}}^{s,t} \qquad \forall (i,j) \in (A - A^D), \forall t \qquad (47)$$

$$u_{r,s,1}^t = \pi_{r,1}^{s,t} \qquad \forall r, \forall s, \forall t \qquad (48)$$

$$x_{i,j,\widetilde{g}}^{s,t} \ge 0 \qquad \forall (i,j) \in A, \forall \widetilde{g}, \forall s, \forall t \qquad (49)$$

$$\pi_{i,\widetilde{g}}^{s,t} \ge 0 \qquad \forall i, \forall s, \forall \widetilde{g}, \forall t \qquad (50)$$

where $b_{i,\widetilde{g}}^{s,t}$ in equation (46) is defined as follows:

$$b_{i,\widetilde{g}}^{s,t} = \begin{cases} -q_{i,s,1}^{t,\widetilde{g}} & \text{if } i \in R \\ 0 & \begin{array}{c}\text{if } i \notin R, i \ne d_1^s \text{ for } \widetilde{g} = 1, \text{and} \\ \text{if } i \notin R, i \ne s \text{ for } \widetilde{g} = 2.\end{array} \\ \sum_{r\in R} q_{r,s,1}^{t,\widetilde{g}} & \begin{array}{c}\text{if } i = d_1^s \text{ for } \widetilde{g} = 1, \\ \text{and if } i = s \text{ for } \widetilde{g} = 2.\end{array} \end{cases} \qquad \forall i, \forall s, \forall t, \forall \widetilde{g} \qquad (51)$$

Similar to the descriptions provided in the AV travel modeling formulation (see Section 3.5.2), constraints (42)-(45) represent the UE conditions for HDV travelers. In particular, constraint (42) guarantees that if HDV travelers with specific destination s patronize link (i, j) in period t, then link (i, j) constitutes a part of the shortest path route for destination s. Further, constraints (43) and (44) ensure that the travel time from destination s or dummy node d_1^s to destination s is zero, respectively, because the dummy node d_1^s represents the destination node s for sub-group 1 HDV travelers. Constraint (45) is similar to constraint (42) but refers to the dummy links, and also has an additional term ρ_k^t, which captures the extra cost that the travelers experience when an intended parking facility is full or if that parking facility is not available for parking. Constraints (46) and (49) are the flow conservation constraints. That is, the inflow to origin node i ($i \in R$) for each destination s, sub-group $\tilde{g}$, and period t is equal to that node's outflow, and the travel demand of sub-group $\tilde{g}$ HDV travelers of origin-destination (r, s) in period t. As the sub-group 1 HDV travelers complete their trips at dummy nodes (d_1^s), the outflow of dummy node d_1^s for destination s in period t is equal to its inflow and the total travel demand of sub-group 1 HDV travelers destined to destination s in period t. Similarly, sub-group 2 HDV travelers finish their trips at the destination node s itself. Finally, the inflow and outflow need to be equal for each of the other nodes in the network. Constraint (47) aggregates the traffic flow of HDV travelers for each destination and user sub-group to obtain the total traffic flow of HDV travelers in each link. Constraint (48) states that the travel cost of user sub-group 1 of HDV travelers for OD pair (r, s) in period t is equal to the travel cost from network node r to destination s for sub-group 1 HDV travelers in that period. Lastly, constraints (49) and (50) guarantee the non-negativity of the decision variables.

3.5.4 Lower-level reformulation

Solving a mathematical program with complementarity constraints can be a cumbersome task. Therefore, the lower-level model was reformulated using the first-order optimality conditions (Karush 2014; Kuhn and Tucker 1951). We prove in Appendix that the solution to the reformulated lower-level model is the same as that for the original lower-level model. The reformulated lower-level model can be written as the following convex and nonlinear program (Equation (52)):

$$\text{Min } Z_L = \sum_{t \in T} \sum_{(i,j) \in A} \int_0^{v_{i,j}^t} \sigma_{i,j}^t(\omega) d\omega \tag{52}$$

Subject to (1), (20), (22), (23), (31)-(36), (39)-(41), (46), (49), (51).

where the objective function (52) is the conventional traffic assignment function. We can then decompose the reformulated lower-level model based on the time periods, which decreases the solving difficulty significantly. The upper-level model is a mixed-integer nonlinear program (MINLP), and the lower-level model is the user equilibrium problem with link capacity constraints. Hence, the combined model is an MINLP which is classified as a non-deterministic polynomial-time hard problem (NP-hard). Ben-Ayed (1990) showed that a bi-level optimization problem is NP-hard even if the objective functions of both levels and all constraints are linear. The next section adopts an efficient solution algorithm to solve the proposed bi-level model.

3.6 Chapter summary

The methodology of this dissertation was presented in this chapter. The bi-level framework was introduced in Section 3.1. Then, initial preliminaries were defined in Section 0. Section 3.3 illustrated the important assumptions of this dissertation in details. Afterwards, the Section 3.4 illustrated the upper-level model and its mathematical formulation. The behavior of the transportation decision maker is modeled via this level. Besides, the Section 3.5 presented the lower-level model which models the travel behavior of the AV and HDV travelers. The components of this model were provided in three parts (Sections 3.5.1-3.5.3), and Section 3.5.4 showed how the lower-level model can be reformulated so that it can be solved more efficiently.

CHAPTER 4. SOLUTION METHODOLOGY

This chapter illustrates an efficient solution methodology to solve the proposed combined parking management problem described in Chapter 3. The proposed model is a mixed-integer nonlinear program with complementarity constraints and is classified as an NP-hard problem. Attempts were made to solve the problem using exact algorithms, but were fruitless due to the complexity of the problem. To address this issue, a particular category of solution algorithms, meta-heuristics, was therefore used to solve the problem efficiently (Bagloee et al. 2018a; b). These techniques are known to compromise global optimality for faster performance, however, they have been shown to be efficacious in identifying near-optimal solutions for large-scale realistic problems with much lower computational cost compared to exact analytical methods (Dokeroglu et al. 2019; Poorzahedy and Rouhani 2007; Ting et al. 2015).

We solve each level of our proposed bi-level model iteratively in this algorithm. Besides, we form a modified version of the upper-level problem (instead of the original upper-level problem) and solve it. The main idea of the algorithm is that an adaptive multi-variate regression function ($\overline{Z}^U$) substitutes the original upper-level objective function (Z^U). This regression function is updated in each iteration of the algorithm based on the last observation. Each observation uses the values of the upper-level decision variables as its inputs, and the resulting original upper-level objective function value as its output. In other words, in this algorithm, we describe the upper-level objective function using the constituent decision variables. Further, we keep the original upper-level constraints to ensure that the new solutions are feasible. Hence, as the algorithm proceeds and more observations are identified, the upper-level description is improved, and because $\overline{Z}^U$ is minimized, superior solutions are obtained.

Let b_0, $\dot{b}_k^t$, and $\ddot{b}_{k,m}^t$ denote the regression model intercept, parking capacity coefficients, and user group-specified parking pricing coefficients, respectively. We also rewrite each Q_k^t into $\varsigma + 1$ binary variables $\dot{Q}_{k,\bar{\varsigma}}^t$ ($\bar{\varsigma} = 0,1, \dots, \varsigma$), and rewrite each $H_{k,m}^t$ into $\varrho + 1$ binary variables $\dot{H}_{k,m,\bar{\varrho}}^t$ ($\bar{\varrho} = 0,1, \dots, \varrho$). This enables us to define a set of constraints that prohibits an already-found solution (Bagloee et al. 2018a). Due to the fact that the already-found solutions are used afterwards to improve $\overline{Z}^U$ and also to derive new results, allowing them to appear again will entrap the solution algorithm in identical solutions. The modified upper-level model (MUL) can be formulated as follows:

$$\text{Min } \overline{Z}^{U} = b_0 + \sum_{t \in T} \sum_{k \in K \cup K'} \dot{b}_k^t \cdot Q_k^t + \sum_{t \in T} \sum_{k \in K \cup K'} \sum_{m \in M} \ddot{b}_{k,m}^t \cdot H_{k,m}^t \tag{53}$$

$$Q_k^t = \sum_{\bar{\varsigma}=1}^{\varsigma} \bar{\varsigma} \times \dot{Q}_{k,\bar{\varsigma}}^t \qquad \forall k \in (K \cup K'), \forall t \tag{54}$$

$$\sum_{\bar{\varsigma}=0}^{\varsigma} \dot{Q}_{k,\bar{\varsigma}}^t = 1 \qquad \forall k \in (K \cup K'), \forall t \tag{55}$$

$$H_{k,m}^t = \sum_{\bar{\varrho}=1}^{\varrho} \bar{\varrho} \times \dot{H}_{k,m,\bar{\varrho}}^t \qquad \forall k \in (K \cup K'), \forall m, \forall t \tag{56}$$

$$\sum_{\bar{\varrho}=0}^{\varrho} \dot{H}_{k,m,\bar{\varrho}}^t = 1 \qquad \forall k \in (K \cup K'), \forall m, \forall t \tag{57}$$

$$\sum_{\dot{Q}_{k,\bar{\varsigma}}^t \in Y1^{iter}} \dot{Q}_{k,\bar{\varsigma}}^t - \sum_{\dot{Q}_{k,\bar{\varsigma}}^t \in Y0^{iter}} \dot{Q}_{k,\bar{\varsigma}}^t + \sum_{\dot{H}_{k,m,\bar{\varrho}}^t \in \widetilde{\overline{Y}}1^{iter}} \dot{H}_{k,m,\bar{\varrho}}^t - \sum_{\dot{H}_{k,m,\bar{\varrho}}^t \in \widetilde{\overline{Y}}0^{iter}} \dot{H}_{k,m,\bar{\varrho}}^t \leq \left|Y1^{iter}\right| - 1 \qquad \forall\, iter \tag{58}$$

$$\dot{Q}_{k,\bar{\varsigma}}^t \in \{0,1\} \qquad \forall \bar{\varsigma} \in \{0,1,\dots,\varsigma\}, \forall k \in (K \cup K'), \forall t \tag{59}$$

$$\dot{H}_{k,m,\bar{\varrho}}^t \in \{0,1\} \qquad \forall \bar{\varrho} \in \{0,1,\dots,\varrho\}, \forall k \in (K \cup K'), \forall m, \forall t \tag{60}$$

and (9)-(17), (19).

where $Y1^{iter} = \{\dot{Q}_{k,\bar{\varsigma}}^t | \dot{Q}_{k,\bar{\varsigma}}^{t,iter} = 1\}$, $Y0^{iter} = \{\dot{Q}_{k,\bar{\varsigma}}^t | \dot{Q}_{k,\bar{\varsigma}}^{t,iter} = 0\}$, $\widetilde{\overline{Y}}\,1^{iter} = \{\dot{H}_{k,m,\bar{\varrho}}^t | \dot{H}_{k,m,\bar{\varrho}}^{t,iter} = 1\}$, and $\widetilde{\overline{Y}}\,0^{iter} = \{\dot{H}_{k,m,\bar{\varrho}}^t | \dot{H}_{k,m,\bar{\varrho}}^{t,iter} = 0\}$. The objective function (53) minimizes the multi-variate regression function $\overline{Z}^{U}$. Constraints (54) and (55) decompose each integer variable (Q_k^t) into a number of binary variables. In other words, if $\dot{Q}_{k,\overline{\varsigma_1}}^t = 1$, Q_k^t will be equal to $\overline{\varsigma_1}$. Besides, $\dot{Q}_{k,\overline{\varsigma_1}}^t = 0$ for $\forall \bar{\varrho} \neq \overline{\varsigma_1}$. Similarly, constraints (56) and (57) rewrite each integer variable ($H_{k,m}^t$) into a number of binary variables. The constraint set (58) ensures that in each iteration, a new solution is obtained for the MUL. Finally, constraints (59) and (60) illustrate the binary domain of the added auxiliary variables.

The modified upper-level objective function ($\overline{\overline{Z}}^{U}$) describes the original upper-level objective function. However, constraint (7) in the original upper-level model (the equity constraint) still cannot be included in the modified upper-level problem ((53)-(58)). To implicitly include this constraint in the MUL, we add the total violation of this constraint (for all origin-destinations and periods) multiplied by a large value $\overline{M}$ as a penalty to the original upper-level objective function's value after solving the decomposed reformulated lower-level problems ($\overline{M} \cdot \sum_t \sum_{(r,s)} \max\left(0, u^t_{r,s,1} - \varphi^t \cdot u^t_{r,s,2}\right)$).

The algorithm flowchart is presented in Figure 9. After setting the iteration counter, an initial feasible solution needs to be found. This initial solution is then used to solve all the decomposed reformulated lower-level problems. Next, given the solution to the lower-level problem, sum of the original upper-level objective function's value and the total equity violation penalty is calculated. Next, if the number of observations is not enough to calibrate a new multi-variate regression function, then a set of random coefficients are produced to be used in the modified upper-level problem objective function. However, if the number of observations is large enough, a new multi-variate regression function is calibrated. Then, the modified upper-level problem is updated and is solved. By solving this problem, a new set of upper-level decision variables' values (δ^{t}_{k}, Q^t_k, and $H^t_{k,m}$) is established which can be used to solve the decomposed reformulated lower-level problems. This process continues until a stopping criterion is met.

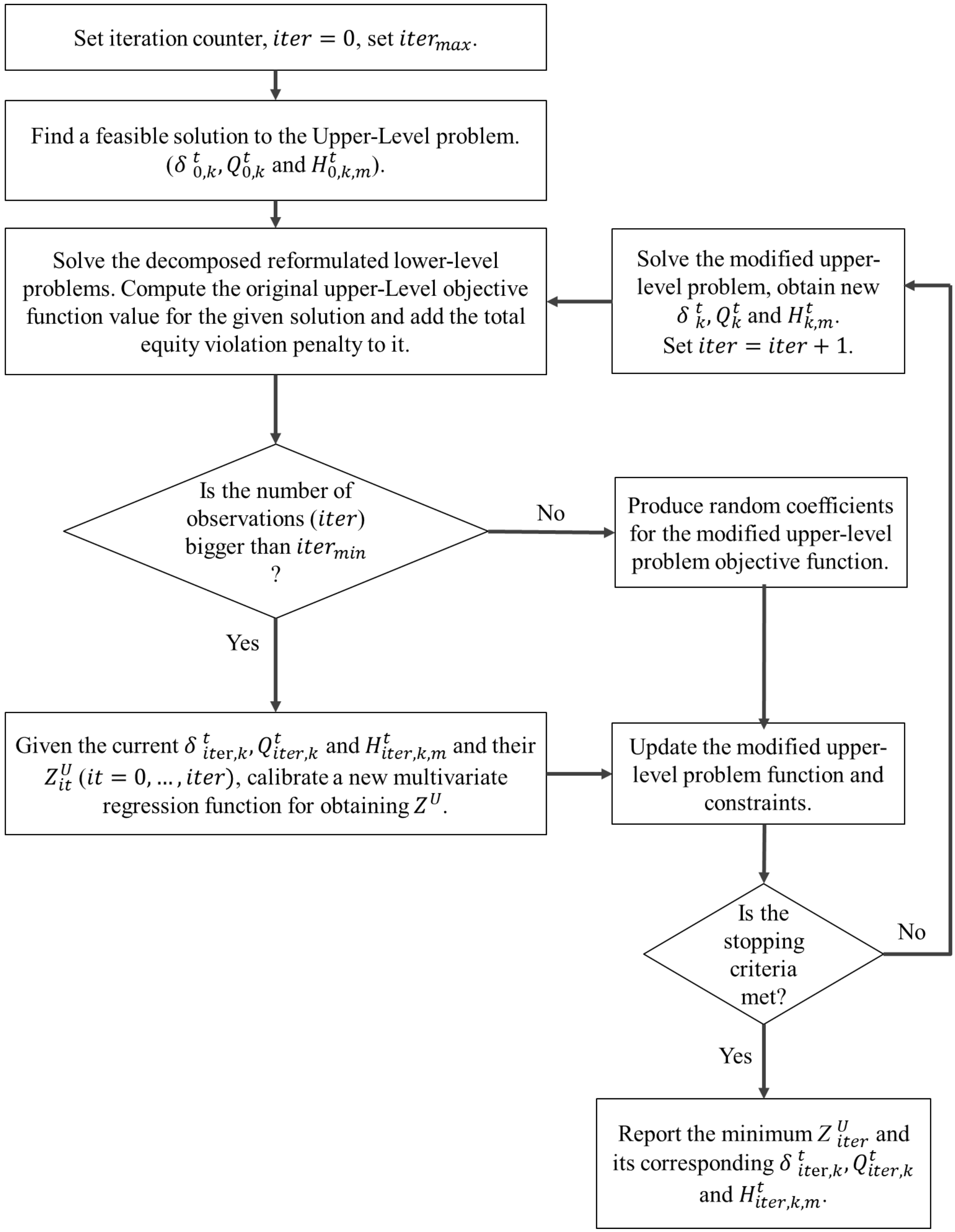


Figure 9. Algorithm flowchart

CHAPTER 5. NUMERICAL RESULTS AND DISCUSSION

This chapter presents the numerical results obtained from testing the proposed framework on the Sioux-Falls, South Dakota network. The Sioux-Falls network (Figure 10) has 24 nodes and 76 links. The characteristics of this network can be found in Leblanc et al. (1975). In order to test the proposed framework, we assume that the shaded area in Figure 10 represents the downtown area. We code the solution algorithm in MATLAB 2018 and General Algebraic Modeling System (GAMS) using CONOPT 4 and CPLEX solvers. We also obtain the results using a Core i7 processor with 2.6 GHZ CPU and 8 GB RAM. The average computational time of the algorithm is 135 minutes.

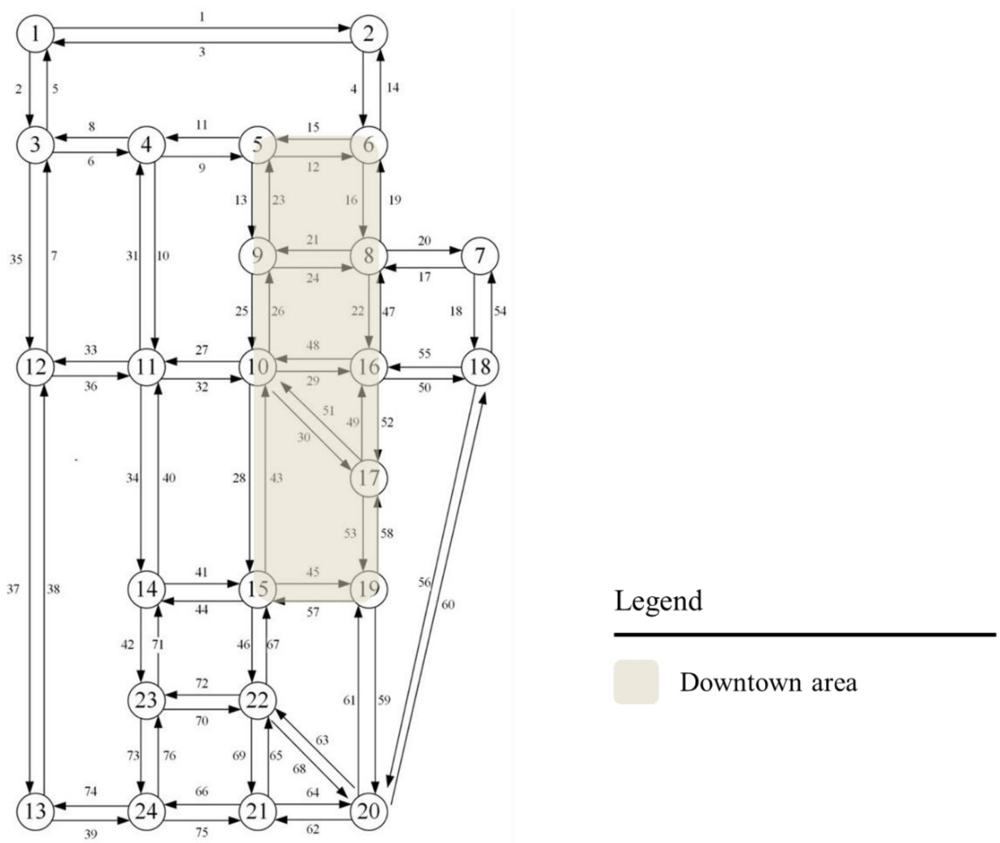


Figure 10. The Sioux-Falls road network

5.1 Case study settings

It is assumed that the planning horizon is 30 years with 6 periods of 5-year duration each. The goal is to obtain the optimal comprehensive parking facility network plan for this urban network through the entire planning horizon, that is, the timings and locations for decommissioning and re-purposing the existing parking facilities and also the timings, locations, and capacities for constructing new parking facilities. The plan also includes the optimal parking fees for AVs and HDVs for each open parking facility in each period. The first 4 periods (i.e., 20 years) are referred to as the "construction horizon" where there exists monetary budget available for constructing the new parking facilities. Further, the last 2 periods (i.e., 10 years) are called the "evaluation horizon" where the long-term impacts of new parking facility construction and also parking facility decommissioning can be observed and evaluated. As shown in Figure 11, the Sioux-Falls network is assumed to have four existing level 3 parking facilities (# 1-4) of which three are located in the downtown area and the fourth is located outside of the downtown area. We have tried to assume similar locations for the parking facilities in Sioux-Falls city as much as possible (Google 2020; "Public Parking - City of Sioux Falls" 2020). It is assumed that there are six potential candidate parking facilities (# 5-10) in the outskirts of Sioux-Falls.

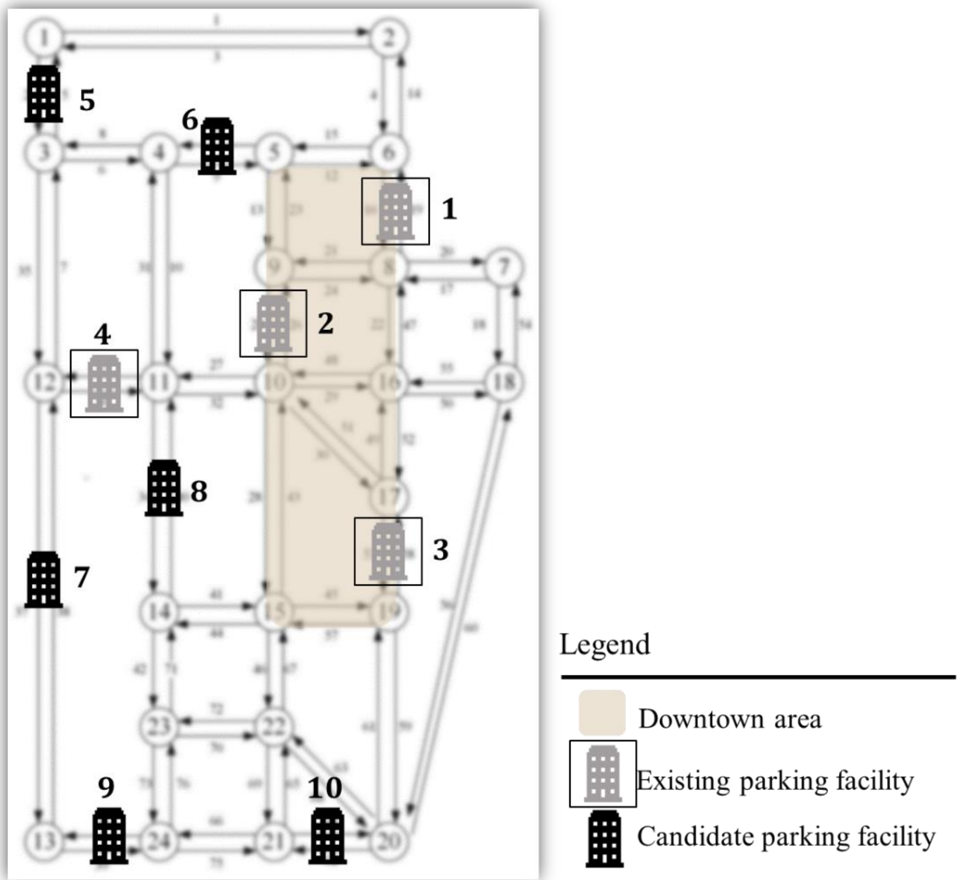


Figure 11. Candidate and existing parking facilities in the Sioux-Falls network

There also exist certain assumed values regarding the parking facility capacities and fees. It is assumed that the transportation decision makers consider three different capacity levels for the new parking facility ($\varsigma = 3$). Further, the given capacity and construction cost (in period 1) of level 1 parking facility are 1,000 vehicles ($\gamma_k^t = 1{,}000, \forall k, \forall t$) and \$20 million dollars ($f_k^{t=1} = \$20\ M, \forall k$), respectively (Rowland 2019). Also, the construction-capacity factor which is used to derive the construction cost level of the parking facilities (ι_1) is considered to be equal to 0.5. In other words, the construction cost of levels 2 and 3 parking facilities with capacities of 2,000 and 3,000 vehicles are equal to \$30 and \$40 million dollars in period 1, respectively. According to Nourinejad et al. (2018), AVs can reduce the parking space requirements up to 87 percent and by 65 percent, on average. Hence, it is assumed that the factor accounting for the AV's requirement of smaller parking spaces compared to HDVs ($\aleph$) (AV parking space reduction factor) is equal to 3. We also consider different levels for the parking fees in each parking facility. The given level 1 parking fee in period 1 is equal to $10 dollars ($\Psi^{t=1} = \$10$), which increases by $1 in each period. Since we consider three levels of parking fee ($\varrho = 3$), the actual parking fees in period 1 can be equal to $10, $20, or $30 dollars in each open parking facility.

We presume that 80 percent of the downtown travelers, regardless of being AV or HDV travelers, do not have parking available at their destinations (i.e., user sub-group $\widetilde{\widehat{g}} = 1$). Besides, the other 20 percent of downtown travelers have their own private parking spots provided at their destinations (i.e., user sub-group $\widetilde{\widehat{g}} = 2$). Downtown travelers are referred to as the travelers whose destination nodes are among the nodes in the shaded area of Figure 10 which includes nodes 5, 6, 8, 9, 10, 15, 16, 17, and 19. The travelers whose trip destinations are not among these nodes are assumed to have parking spots available at their destinations. In other words, they are all included in user sub-group $\widetilde{\widehat{g}} = 2$. Besides, the total travel demand for each origin-destination in period 1 follows the values reported in Leblanc et al. (1975) multiplied by two in order to account for the travel demand growth since 1975 (Chakirov and Fourie 2014; Chow et al. 2010), and increases by 5 percent in each period. The value of time for HDV and AV travelers are assumed to be equal to $20 and $10 dollars in period 1, respectively. This value is increased by $1 in each period. The interest rate is assumed to be 5 percent for each period. There is also an assumption regarding the value of the relative walking discomfort compared to driving ($\bar{g}$). We consider this value to be equal to 3, which means that 3 minutes of walking and 1 minute of driving have a same discomfort for the HDV travelers.

5.2 Benchmark settings and solution

In the base analysis, the construction budget for constructing new parking facilities (B^t) is assumed to be $40 million dollars in each of the first 4 periods ($B^t = \$40\ M, \forall t \leq 4$). We investigate different construction budget levels in Section 5.3. Further, the monetary benefits of decommissioning and re-purposing each existing parking facility are assumed to be equal to $54 million dollars in the first period ($\omega_k^{t=1} = \$54\ M, \forall k$) which is assumed to increase according to the construction price index in each period. We choose this value because a level 3 parking facility, with a capacity of 3,000 vehicles and a $20 parking fee, makes $54 million dollars in each period if it is used to exactly half of its full capacity. The analysis in Section 5.4 investigates the problem for different values of this parameter. We also assume that the penetration rate of AVs is equal to 5 percent in the first period, increases by 10 percent in each period, and reaches to 55 percent in period 6 (Bansal and Kockelman 2017). Due to the high degree of uncertainty regarding the future of AVs, we also assess two other incremental increase trends for AV penetration rates (Section 5.5). Figure 12 illustrates the variations of the most superior values of the upper-level objective function over the iterations for the base analysis. As can be seen in this figure, although there are some slight improvements in the first 250 iterations (the calibration part), significant drops are observed after iteration 250 where the modified upper-level objective function's parameters are derived through fitting a multi-variate regression function.

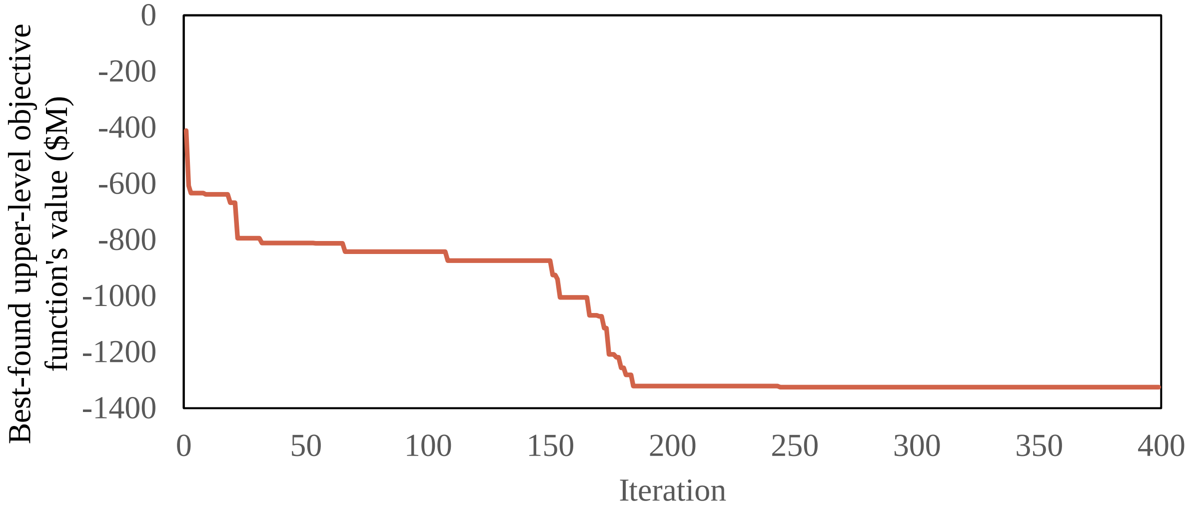


Figure 12. Variations of the most superior value of the upper-level objective function (for benchmark settings of the problem)

Figure 13 and Table 3 present the results. According to Figure 13, in period 1, parking facilities #6 and #8 with level 1 capacity should be constructed. Further, in period 2, another level 1 parking facility (parking facility #9) should be constructed, while parking facility #4 need to be decommissioned and repurposed. Besides, parking facilities #5 and #10 with level 1 capacity should be constructed in periods 3 and 4, respectively. In period 5, parking facility #2 need to be decommissioned. The optimal differentiated location-based parking fees for AVs and HDVs in each period are summarized in Table 3. It is interesting to note is that the established parking fees for downtown parking facilities (#1-3) are at their maximum levels for HDVs and AVs in periods 1-4. However, the parking fee levels for HDVs in these locations decrease in periods 5 and 6 due to the decommissioning of parking facility #4. The HDV travelers that used to park in parking facility #2 now want to park in facilities #1 and #3 that may not be preferable for them. Hence, the model prescribes these decreases to account for the increased travel costs of those travelers and so that the equity constraints are not violated. Besides, the fees in parking facility #8 are set so that HDV travelers pay a lower price compared to AVs (one-third). This will motivate AVs to park in farther locations (parking facilities #5, #9, and #10) where the fees are lower for AVs (one-half).

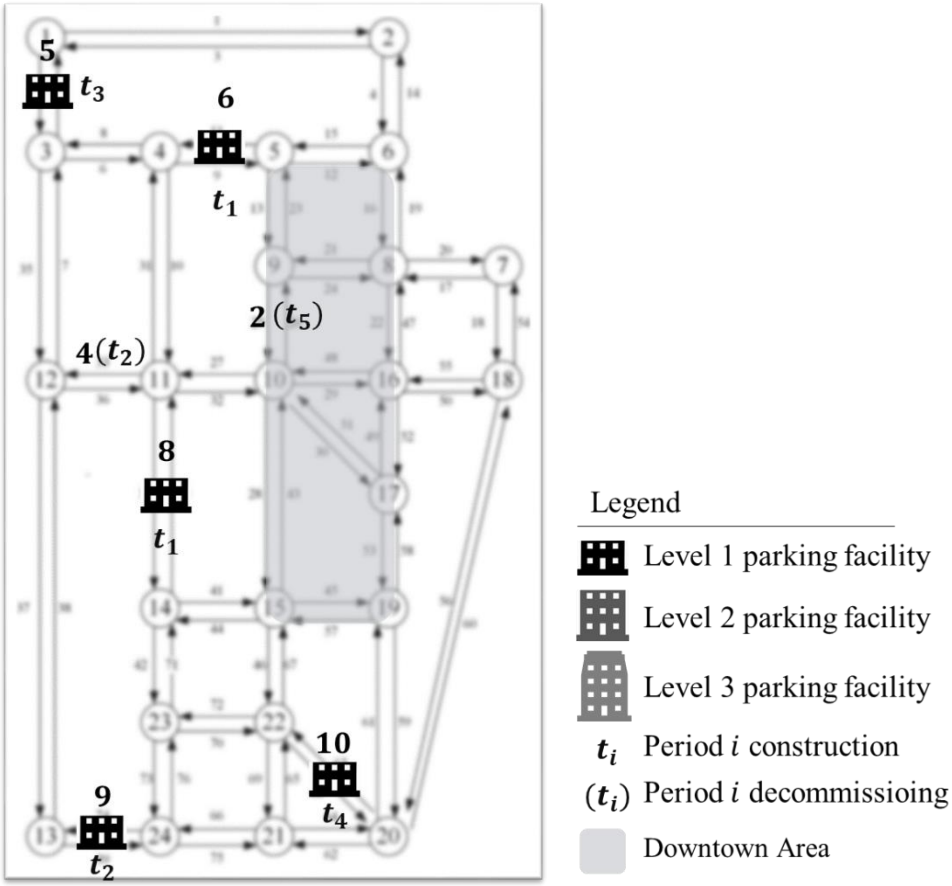


Figure 13. Optimal timings, locations, and capacities for constructing and decommissioning the parking facilities (for the given problem benchmark settings).

Table 3. Model described parking fee levels for HDVs and AVs at the various parking facilities (for the given problem benchmark settings).

Parking facility	Period					
	1	2	3	4	5	6
1	3,3	3,3	3,3	3,3	2,3	2,3
2	3,3	3,3	3,3	3,3	-	-
3	3,3	3,3	3,3	3,3	2,3	2,3
4	3,1	-	-	-	-	-
5	-	-	2,1	2,1	2,1	2,1
6	2,3	2,3	2,3	2,3	2,3	2,3
7	-	-	-	-	-	-
8	2,3	1,3	1,3	1,3	1,3	1,3
9	-	2,1	2,1	2,1	2,1	2,1
10	-	-	-	2,1	2,1	2,1

5.3 Sensitivity analysis on the construction budget level

The first sensitivity analysis is conducted on the construction budget level. We also show the algorithm performance in terms of the most superior solution in this section. As mentioned above, the construction budget is assumed to be \$40 million dollars in each of the first 4 periods in the base analysis in section 5.2. We also run the framework for \$0, \$20, \$60, and \$80 million dollars and compare the results. \$0 million dollars accounts for the case that there is no budget available for constructing new parking facilities. Figure 14 reports the variations of the most superior values of the upper-level objective function through the iterations for different construction budget levels. Similar to Figure 12, there exist some minor improvements in the value of the upper-level objective function in the first 150 iterations. However, significant improvements are observed in latter iterations.

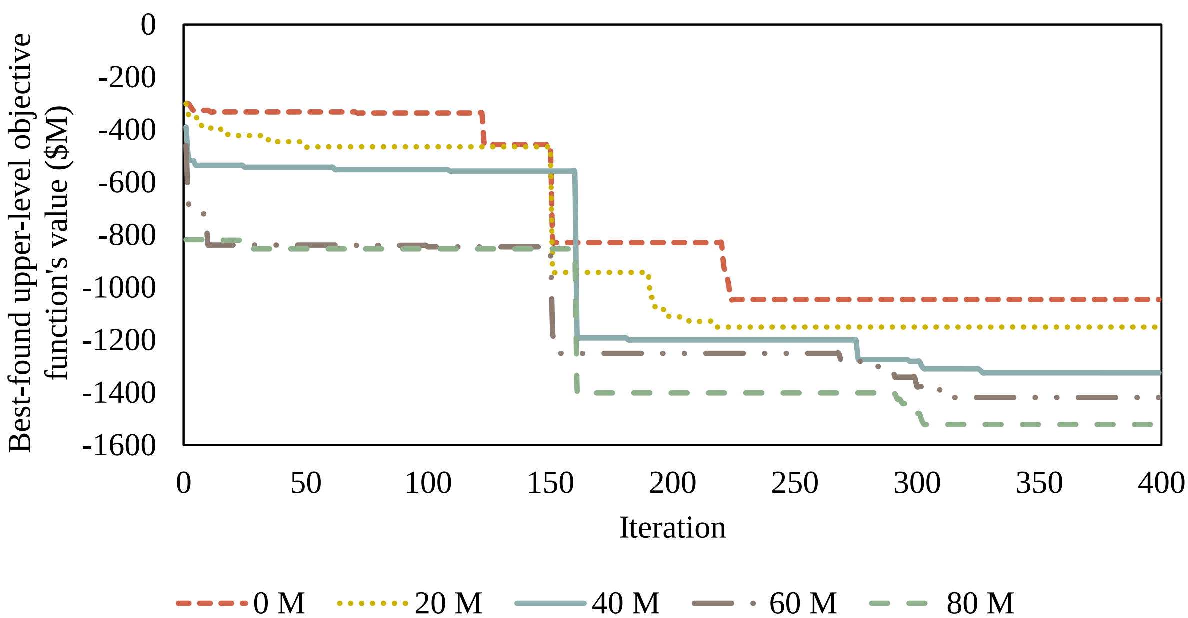


Figure 14. Variations of the best value of the upper-level objective function for different levels of construction budget

Table 4 presents the numerical results for different network performance measures for different values of construction budget. There is a clear trend of upper-level objective function's value (Z^U) decreasing as the construction budget is increased. This is theoretically expected because increasing the construction budget (B^t), that is the right-hand side of equation (9) in the upper-level problem, will enlarge the feasible region and superior solutions can be obtained. This improvement is achieved in this problem by more parking facility construction and more parking facility decommissioning. The monetary benefits of parking facility decommissioning contribute heavily to the value of the upper-level objective function.

Table 4. Numerical results for different values of construction budget (in $M)

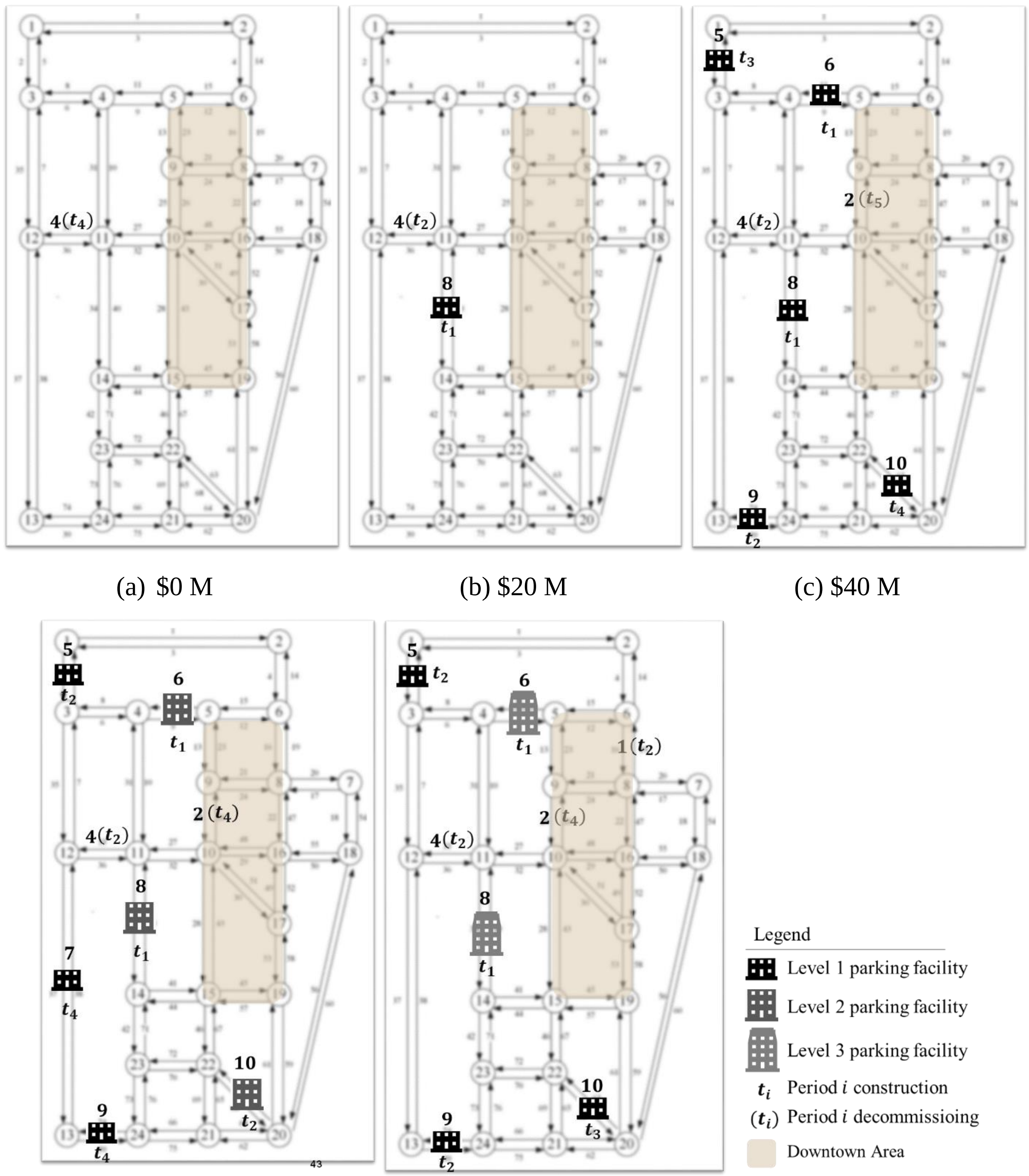
Construction budget in each period	Upper-level objective function value	Cost of total system travel time	Total decommissioning benefits	Total parking fee revenues	Total construction cost
0	-1,045.89	334.27	197.07	1,183.09	0
20	-1,150.73	312.54	313.30	1,157.77	20.00
40	-1,325.01	301.98	447.86	1,179.13	106.20
60	-1,418.52	334.60	579.29	1,173.84	156.60
80	-1,521.36	359.92	707.44	1,173.84	167.20

Interestingly, the cost of total system travel time, which is the sum of in-vehicle and out-of-vehicle travel cost of the travelers, first decreases slightly as the construction budget increases. It reaches its minimum with the moderate budget of 40 million dollars in each period. Then, it increases in higher budget levels. The initial decrease is due to the fact that as the budget increases from 0 to 40 million dollars, more new parking facilities can be constructed (the total construction cost increases), however, there still exists little parking facility decommissioning in the downtown area and the HDV travelers are not affected severely. As the budget increases from 40 to 80 million dollars, it will be possible to decommission more parking facilities in the downtown area which has significant monetary benefits. Consequently, higher amount of parking facility decommissioning causes increases in the cost of total system travel time since the HDV travelers need to traverse longer distances (more last-mile travel cost) to reach their destinations. This is also why the total decommissioning benefits increases significantly as the budget increases.

Closer inspection of the table shows that since with 20 million dollars in each period, we only can construct one level 1 parking facility in the first period, the results for 0 and 20 million dollar budgets are not significantly different. As we can have much more new parking construction with 40 million dollars of budget, the measures show significant changes compared to the 20 million dollars of budget. In fact, the transportation decision makers can earn more than 156 million dollars (in terms of parking facility decommissioning and parking fee revenues) and by investing 86 million dollars for constructing new parking facilities in the outskirts.

Figure 15 illustrates the optimal timings, locations, and capacities for constructing and decommissioning parking facilities for different values of construction budget in each period. It is apparent from this figure that as the construction budget increases, there are more new parking facility construction and more parking facility decommissioning. A comparison of Figure 15.a and Figure 15.b reveals that both plans prescribe the decommissioning of parking facility #4. However, due to the fact that we are able to construct a level 1 parking facility in $20 million budget scenario, it is possible to decommission the parking facility #4 sooner (in period 2 instead of period 4). However, one unanticipated finding is that even without any new parking facility construction with zero construction budget, we are able to decommission one parking facility in period 4. This observation is related to the AV's requirement of smaller parking spaces compared to HDVs. In period 4 that the parking facility #4 is decommissioned, the AV penetration rate reaches 35 percent and we are able to decommission and repurpose one parking facility. Another interesting observation to emerge from this figure is that the parking facility located outside of the downtown area is the first parking facility to decommission in all construction budget levels because of being less critical compared to the other parking facilities. Further, comparing the results of Figure 15c-e with higher construction budget levels shows that it is recommended to construct larger parking facilities (#6 and #8) in outskirt areas relatively close to the downtown area, and then construct smaller parking facilities in the relatively farther areas (#7, #9, and #10). This can be explained by the fact that HDV travelers can access the parking facilities relatively close to the downtown area after those in the downtown are decommissioned in order to keep the last-mile travel costs low. Further, AVs which also require less parking spaces can be sent to new small-sized parking facilities at farther locations.

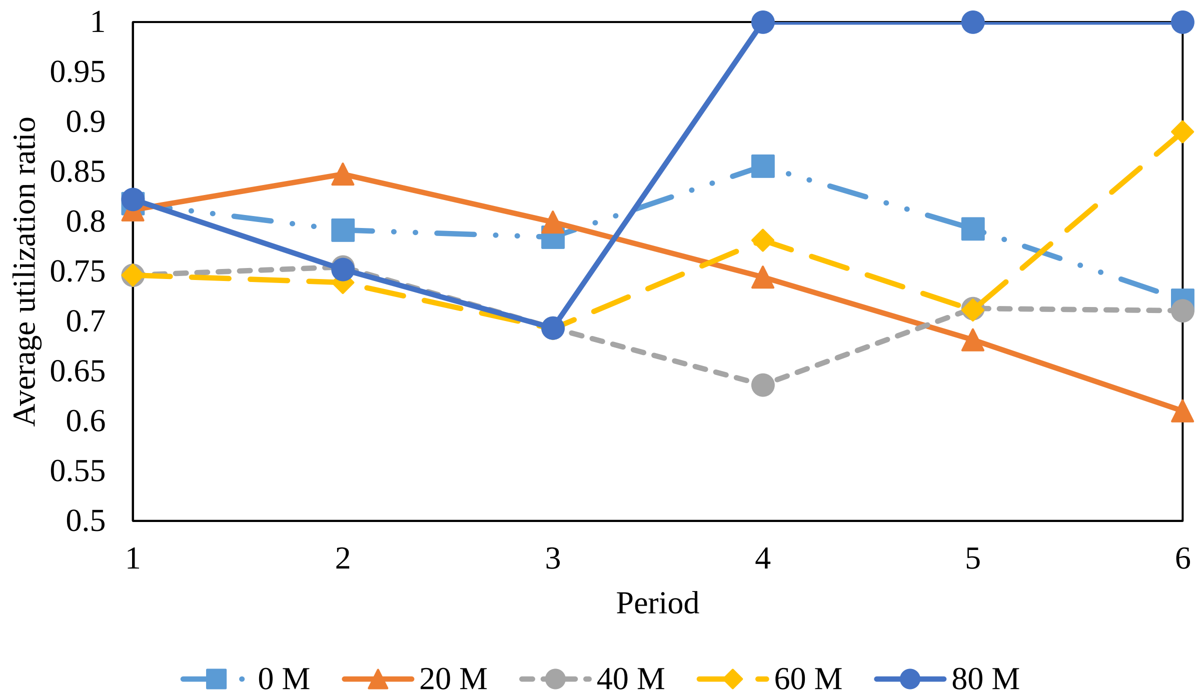
Figure 16 presents the average utilization ratio of active downtown and out-of-downtown parking facilities through the planning horizon for different values of construction budget in each period. This figure is revealing in several ways. First, in \$40M and \$60M budget scenarios, the average utilization ratio of downtown parking facilities increases significantly in the latter periods. This increase is due to the fact that the number of open downtown facilities is decreased gradually while there is still demand for it. Second, we can also examine the scenarios involving \$0M and \$20M budget where no downtown parking facility decommissioning is conducted in the entire planning horizon. In these scenarios, the average utilization ratio decreases in overall which is due to the AV's requirement of less parking spaces compared to HDVs. Third, as shown in Figure 16b, the average utilization ratio of out-of-downtown parking facilities for the scenario with zero budget decreases gradually until period 3 when the only available parking facility is decommissioned (parking facility #4). However, in the one with \$20M construction budget, the ratio increases to 1 in period 2 and stays at that level until end of the planning horizon. This is because in this scenario, level 1 parking facility #8 is constructed in period 1 and parking facility #4 is decommissioned in period 2. Further, a closer look at Figure 16b shows that the ratio increases in the earlier periods due to the downtown parking facility decommissioning, and then it shows small fluctuations in rest of the planning horizon.



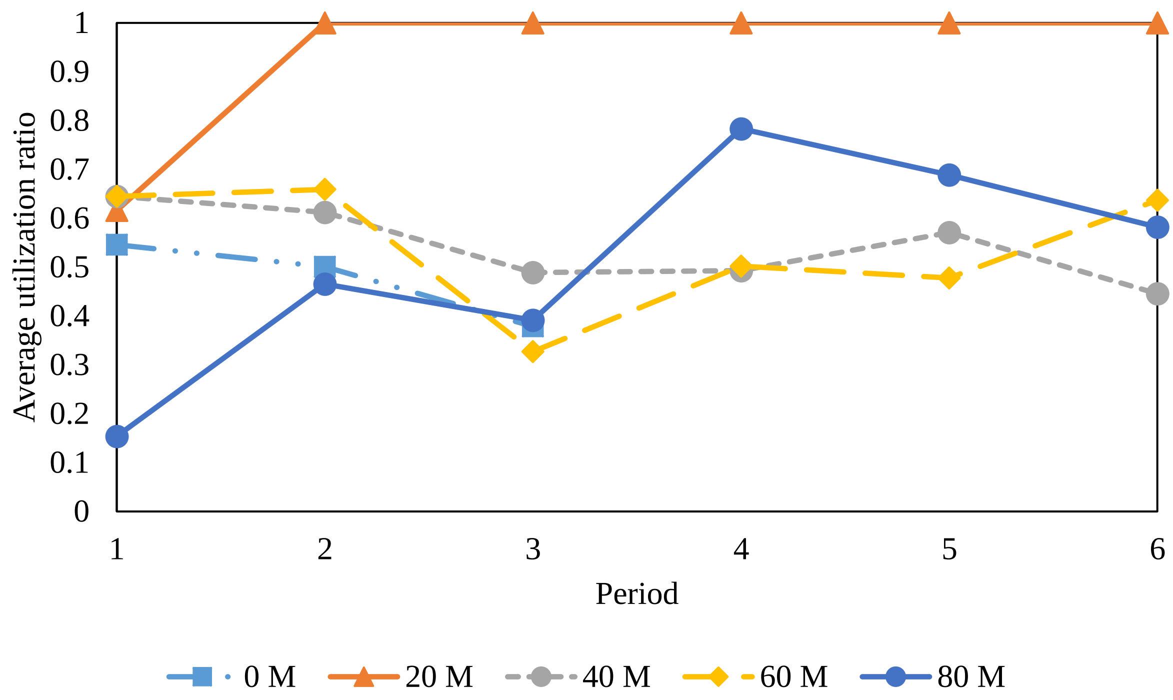
(a) \$0 M (b) \$20 M (c) \$40 M

(d) \$60 M (e) \$80 M

Figure 15. Optimal timings, locations, and capacities for constructing and decommissioning parking facilities for different values of construction budget in each period



(a) Downtown parking facilities



(b) Out-of-downtown parking facilities

Figure 16. Average utilization ratio of parking facilities for different values of construction budget in each period

5.4 Sensitivity analysis on the rate of parking facility decommissioning benefits

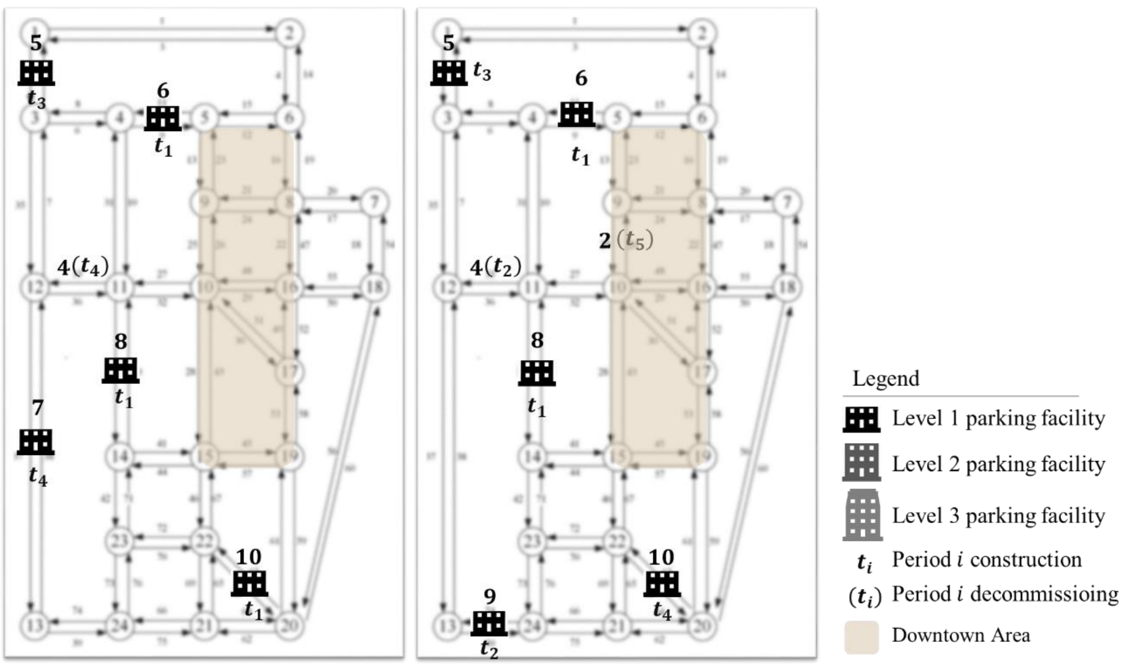
This set of analyses examines the impact of monetary benefits of parking facility decommissioning on the problem solution. This benefit can vary significantly for different new land uses. The new land use could be green space, a park, a multi-purpose building with housing, gym, business offices, and so on. Hence, the amount of monetary benefits can be significantly different. Besides, it may not be very easy to monetize all of the benefits that the facility can bring to the community. This leads us to obtain the results for different values of these monetary benefits to investigate how the optimal solution varies. As in the benchmark setting, the initial rate is set to $54 million dollars, we obtain the results for $5, $10, and $100 million dollars beside it. It should be noted that the considered budget for constructing new parking facilities is equal to $40 million dollars in each period in this analysis. Besides, the penetration rate of AVs starts at 5 percent in period 1, increases by 10 percent in each period, and reaches to 55 percent in period 6.

Surprisingly, the proposed plan is the same when the rate is greater than or equal to $10 million dollars. What differs among these cases is the total decommissioning benefits, and consequently, the resulting upper-level objective function's value. In other words, the cost of total system travel time, the total parking fee revenues, and the total construction cost are similar when the rate is greater or equal to 10 million dollars. This is because the identified timings, locations, and capacities for constructing or decommissioning parking facilities, and the differentiated parking fees are the same when the initial rate of parking facility decommissioning is greater than $10 million dollars.

Table 5. Numerical results for different values of initial parking facility decommissioing benefits (in $M)

Initial rate of parking facility decommissioning benefits	Upper-level objective function value	Cost of total system travel time	Total decommissioning benefits	Total parking fee revenues	Total construction cost
5	-927.07	265.02	18.25	1,173.84	106.20
10	-935.17	301.98	58.02	1,179.13	106.20
54	-1,325.01	301.98	447.86	1,179.13	106.20
100	-1,706.52	301.98	829.37	1,179.13	106.20

Figure 17 compares the optimal identified solutions for different values of initial rate of parking facility decommissioning benefits. As discussed above, there are fewer parking facility decommissionings in the case with $5 million dollars compared to the case with $10 million dollars or more. It is interesting to note that the proposed parking decommissioning plan for the case with $5 million dollars of benefits is similar to the case in which no new parking facility construction is possible (Figure 15a) but the rate of decommissioning benefits is 54 million dollars in period 1.



(a) $5M (b) ≥ $10M

Figure 17. Optimal timings, locations, and capacities for constructing or decommissioning parking facilities for different values of initial rate of parking facility decommissioning benefits

5.5 Sensitivity analysis on the AV penetration rate trend

The last set of analyses assess the impacts of different AV penetration rate (AVPR) trends on the long-term performance of the transportation system. This set of analysis is necessary as AVs' future is very uncertain (Litman 2020; Saeed et al. 2020). For instance, a simulation-based study by Bansal and Kockelman predicts that AVs in U.S. will have 24% penetration by 2045 under pessimistic scenarios and up to 87% under optimistic scenarios (Bansal and Kockelman 2017).

Hence, we conduct two other analyses on the AVPR trends beside the one used in the other parts of this chapter. While we assume that the initial AVPR is equal to 5 percent, grows by 10 percent in each period, and reaches 55 percent in the benchmark analysis, we also conduct the analysis for the growth rate of 5 and 15 percent. Table 6 presents the numerical results for different AVPR trends. There are correlations between the incremental increase in the AVPR and the cost of total system travel time and total parking fee revenues are remarkable results. These correlations are due to the fact that as the total penetration rate of AVs increase in the network, the travelers are expected to save more on the last-mile travel cost since they can be dropped off at their destinations. Besides, AVs are parked mostly in the outskirts of the cities with lower parking fees. Hence, the total parking fee revenues decrease as well when the AVPRs increase. Further, the total construction cost decreases in the last two scenarios as due to the AVs' requirement of smaller parking spaces compared to HDVs, it is possible to construct smaller-sized parking facilities.

Table 6. Numerical results for different AV penetration rate trends (in $M)

AVPR (%)			Objective function value	Cost of total system travel time	Total decommissioning benefits	Total parking fee revenues	Total construction cost
Initial	Growth rate	Final					
5	+5	30	-1,468.95	336.74	447.86	1,356.84	128.28
5	+10	55	-1,325.01	301.98	447.86	1,179.13	106.20
5	+15	80	-1,284.99	239.40	447.86	1,076.53	106.20

The study also examined variations in the cost of total cost of system travel time over the time periods for different AVPR trends in Figure 18. As illustrated in this figure, as the growth rate of AVPR increases, the cost of total system travel time in each period decreases. In all 3 cases, the cost of total system travel time increases until period 4. This increase is attributed mainly to the increases in the total travel demand. However, after period 4, we have decreases in the case with 10 percent of AVPR growth rate and also in the case with 15 percent of AVPR growth rate.

This decrease is due to the higher AV penetrations in the network. For instance, in the case with 15 percent of AVPR growth, the AVPR in period 4 is exactly 50 percent. As the rate goes beyond 50 percent, we see a significant decrease in the total system travel cost despite the overall increase in travel demand. It is interesting to note that in the case with 5 percent of AVPR growth rate, we see significant increases in total system travel time in period 6 which is due to the overall travel demand increase. The significant increase is also, in part, due to the traffic congestion in the network which is reaching its capacity and can cause lower level of service. With this in mind, we can see how more AVPR trends are avoiding that increase and even result in less total system travel costs.

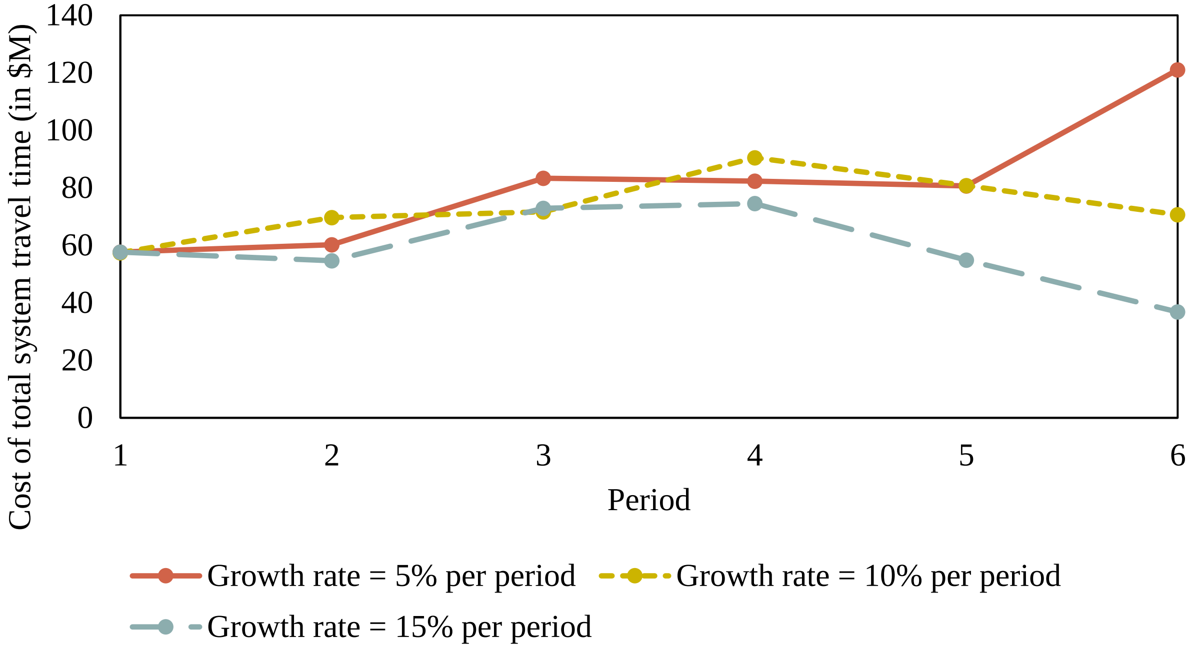


Figure 18. Total system travel cost for different AV penetration rate trends over the planning horizon

Finally, the study also assessed the variations in the total parking fee revenues over time for different AVPR trends (Figure 19). As discussed above, the total parking fee revenues decrease as the penetration rate of AVs increases. This difference is even more highlighted in the latter periods where the differences in AVPRs become larger. Further, the fluctuations are quite different for each case. In the case with 15 percent of AVPR growth rate, we see consistent decreases over time which becomes even more severe in the last period. This is due to the significant increases in

AVPRs in this case. As the AVPRs increase, more AVs are parked in the outskirts of the city which also want to pay less for parking. The overall decreasing trend is also observed for the one with 10 percent of AVPR growth rate, but it fluctuates more severely compared to other cases. The different trend is in part, due to the slightly different proposed parking facility decommissioning plan compared to the case with 15 percent of AVPR growth rate as well. In the smallest AVPR growth rate, the total parking fee revenues increase gradually as the total travel demand increases, however, it decreases significantly in the last period as well because the effect of increased AVPR is finally bigger than the increases in the travel demand.

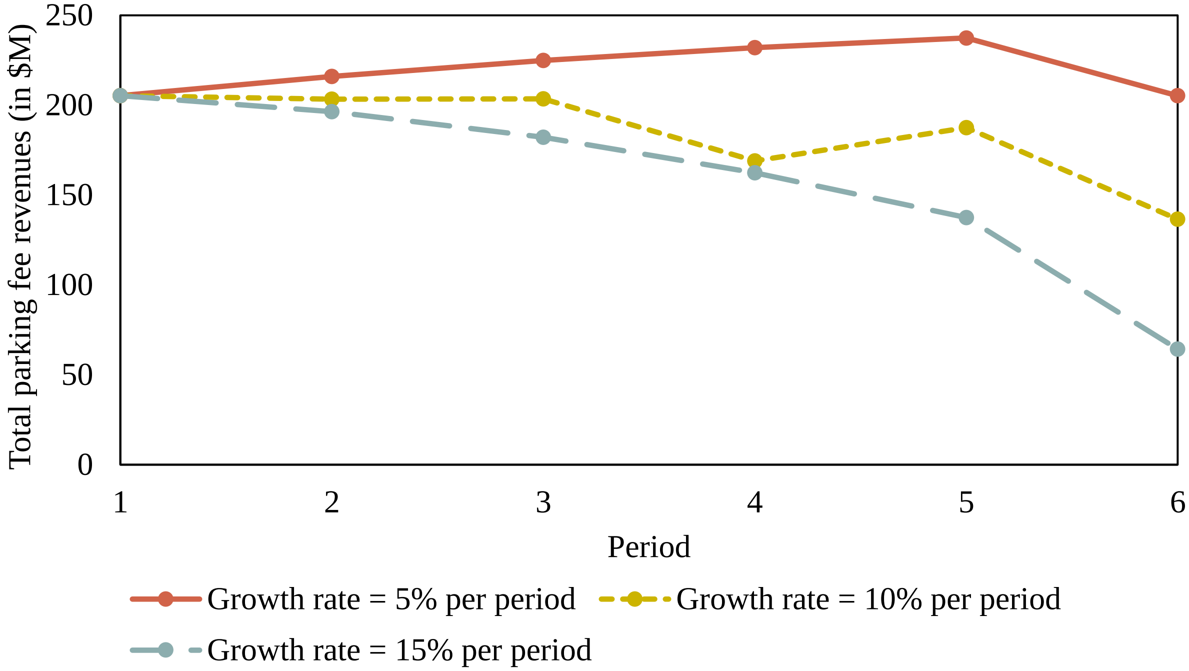


Figure 19. Total parking fee revenues for different AV penetration rate trends over the planning horizon

CHAPTER 6. CONCLUDING REMARKS

This chapter summarizes the dissertation, highlights its contributions and findings, and suggests a number of possible directions for future research based on its limitations and potentials.

6.1 Summary

The main purpose of the current dissertation was to provide a comprehensive framework to determine the timings, locations, and capacities for constructing new parking facilities and decommissioning and repurposing existing parking facilities for a mixed fleet of human-driven vehicles (HDVs) and autonomous vehicles (AVs). The objectives of this study were also to minimize the total system travel cost of the travelers (sum of the in-vehicle and out-of-vehicle travel cost), to maximize the total parking fee revenues, and to maximize the monetary benefits of repurposing the existing parking facilities. These objectives were included as the system-level goals of the transportation decision makers in the upper-level model. Besides, in the lower-level model, the AV and HDV travelers (two user groups) sought to minimize their total travel costs. In each user group, there were assumed two sub-user groups based on the parking space availability at their destination. The travel cost of travelers with parking space available at their destination only included the in-vehicle travel cost from their origin to their destination. Besides, for AV travelers without parking spaces at their destination, the travel cost included the in-vehicle travel cost from origin to the destination, AV operation cost for the trip between their destination and the selected parking facility, and the AV-specified parking fee. For HDV travelers without parking spaces, the travel cost included the in-vehicle travel cost from the origin to their selected parking facility, the HDV-specified parking fee and the last-mile travel cost.

6.2 Findings and conclusions

The proposed framework was tested on the Sioux-Falls network and the algorithm was shown to be capable of finding the optimal solution in an efficient manner. The numerical experiments suggested that in high construction budget levels, more parking facility decommissioning is proposed because the decommissioned facilities can be replaced with new facilities in the outskirts of the city. Consequently, the monetary benefits of decommissioning existing parking facilities increase significantly as the budget increases. The findings also suggest that more parking facility construction in the outskirts results in increases in the total system travel cost (the sum of in-vehicle and out-of-vehicle travel cost) due to increases in the last-mile travel costs of the HDV travelers. It was also found that even if there is no monetary budget available for constructing new parking facilities, it is still optimal to decommission some of the existing downtown parking facilities at a time of high AV penetration due to AV's requirement of smaller parking spaces compared to HDVs. Another significant finding of this study is that large-sized new parking facilities should be constructed close to the downtown area to accommodate the parking needs of HDV travelers, while in farther locations, small-sized parking facilities should be constructed to satisfy the parking needs of AVs which is also due to the fact that AVs require smaller parking spaces compared to HDVs.

Further analyses on the rate of parking facility decommissioning benefits concluded that similar parking facility decommissioning plans are proposed when the rate of these benefits for decommissioning each parking facility is larger than a relatively low minimum value. Further investigations also revealed that notwithstanding the growth in total travel demand, the total cost of the travelers and total parking fee revenues decrease significantly as the penetration rate of AVs in the network increases.

6.3 Contributions

This dissertation provided a multi-period methodology in which the transportation decision makers can address the urban parking issue in the presence of AVs and HDVs in the long term. This methodology enables them to locate new parking facilities, decommission the existing parking facilities for more efficient land uses, set the parking fee of these parking facilities, and investigate the long-term impacts of their decisions on the performance of the transportation network. Besides, this dissertation developed a parking pricing strategy to keep the HDV-AV travel cost ratio (HATCOR) to a pre-specified threshold to maintain the social equity by suggesting different parking fee for AVs and HDVs in each parking facility.

6.4 Limitations

One limitation of this study is that it did not consider the uncertainties in projections of the AV penetration rates (AVPRs). Although the author has investigated different AVPR trends in Section 5.5, however, the AVPR uncertainties have not been considered directly in the modeling framework. Besides, this study does not account for the travel demand elasticity. In other words, although the travel demands of HDV and AV travelers change in each period, the fluctuations in the travel cost and parking facility locations do not affect them. Another limitation of this dissertation is that it does not consider the on-street parking while it impacts the traffic congestion enormously in some metropolitan areas. Further, this study was limited by the absence of shared AVs. Although some researchers believe that most of the AVs in future will be private (Saeed et al. 2020), however, shared AVs will also constitute a significant proportion of AVs and their parking needs might be different to those of private AVs. Besides, another limitation of this study is that the utilized algorithm calibrated a linear regression function to substitute the original upper-level objective function. However, the relationship between the upper-level decision variables and the upper-level objective function might not follow a linear relationship. Further, this study considers AVs but it did not account for their connectivity which could impact their travel behavior significantly (Dong et al. 2020b; a; Labi et al. 2019; Niroumand et al. 2020). Besides, this study did not consider the potential interactions of HDVs and AVs and only considered their simultaneous presence which could also impact the transportation network performance (Li et al. 2020b; a). Last but not least, although the proposed framework has tried to consider the social equity considerations by not allowing the travel cost of HDV travelers to increase beyond certain thresholds, a probable shift of wealth is observed in some of the results especially in high construction budget levels from travelers to the transportation agency and the private sectors. In these cases, although a high amount of parking facility decommissioning and re-purposing has resulted in significant monetary benefits for transportation decision makers, however, it has also increased the travel costs of HDV travelers.

6.5 Future work

The findings of this dissertation provide several insights for the future research. First, although we analyzed the impacts of different AV penetration rate trends, a further study could develop a robust parking facility location problem to account for the long-term uncertainties in the AVPRs and considering worst-case travel demand scenarios in the long-term (Miralinaghi and Peeta 2019; Tabesh et al. 2019b). Second, a natural progression of this dissertation is to consider the on-street parking. Doing so, the impacts of repurposing the on-street parking spaces for other land-uses such as active transit or even an extra traffic lane could also be assessed. Third, further work is also needed to consider shared AVs in order to fully understand the implications of AVs in the transportation network. Fourth, instead of a multi-variate linear regression function in the algorithm, one can use other more sophisticated machine learning techniques. Further research in this field can provide efficient solution algorithms for tackling different variants of bi-level optimization programs.

6.6 Final remarks

This dissertation began with a comprehensive discussion of the parking issue in downtown areas and how the AVs could help to alleviate some of these problems. The opportunities and challenges that AVs introduce to the transportation network were discussed thoroughly. Then, the academic literature on the parking facility location problem and the AV parking impacts on traffic were discussed. Then, a bi-level framework was introduced to locate and decommission the parking facilities and their fees for a mixed fleet of AVs and HDVs. Afterwards, a solution algorithm was presented to solve the introduced mathematical program. Then, the numerical results for the Sioux-Falls network were presented and discussed. Finally, the concluding remarks summarized the study, contributions, findings, and limitations, and proposed some directions for future work.

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APPENDIX

We show that the solution to the lower-level problem is equivalent to the following problem. Note that $\lambda_{i,\widehat{g}}^{s,t,1}$, $\lambda_{i,1}^{d_2^s,t,2}$, $\pi_{i,\widehat{g}}^{s,t}$, ρ_k^t, $\psi_{i,j,\widehat{g}}^{s,t}$, $\dot{\psi}_{i,j}^{s,t}$, and $\ddot{\psi}_{i,j,\widehat{g}}^{s,t}$ are the dual variables associated with constraints (62)-(69), respectively.

$$\text{Min } Z_L = \sum_{t\in T}\sum_{(i,j)\in A}\int_0^{v_{i,j}^t}\sigma_{i,j}^t(\omega)d\omega \tag{61}$$

$$\sum_{j:(j,i)\in A} y_{j,i,\widehat{g}}^{s,t,1} - \sum_{j:(i,j)\in A} y_{i,j,\widehat{g}}^{s,t,1} - \bar{b}_{i,\widehat{g}}^{s,t} = 0 \qquad \forall i, \forall s, \forall \widehat{g}, \forall t \qquad \lambda_{i,\widehat{g}}^{s,t,1} \tag{62}$$

$$\sum_{j:(j,i)\in A} y_{j,i,2}^{d_2^s,t,2} - \sum_{j:(i,j)\in A} y_{i,j,2}^{d_2^s,t,2} - \bar{\bar{b}}_i^{d_2^s,t} = 0 \qquad \forall i, \forall s, \forall t \qquad \lambda_{i,1}^{d_2^s,t,2} \tag{63}$$

$$\sum_{j:(j,i)\in A} x_{j,i,\widehat{g}}^{s,t} - \sum_{j:(i,j)\in A} x_{i,j,\widehat{g}}^{s,t} - b_{i,\widehat{g}}^{s,t} = 0 \qquad \forall i, \forall s, \forall \widehat{g}, \forall t \qquad \pi_{i,\widehat{g}}^{s,t} \tag{64}$$

$$Q_k^t \cdot \gamma_k^t - \sum_{s\in S} x_{k,d_1^s,1}^{s,t} - \frac{1}{\aleph}\cdot\sum_{s\in S} y_{k,d_2^s,1}^{d_2^s,t,2} \geq 0 \qquad \forall k, \forall t \qquad \rho_k^t \tag{65}$$

$$x_{i,j}^t - \sum_{\widehat{g}\in\widehat{G}}\sum_{s\in S} x_{i,j,\widehat{g}}^{s,t} - \sum_{\widehat{g}\in\widehat{G}}\sum_{s\in S} y_{i,j,\widehat{g}}^{s,t,1} - \sum_{s\in S} y_{i,j,2}^{d_2^s,t,2} = 0 \qquad \forall (i,j)\in A, \forall t \tag{66}$$

$$y_{i,j,\widehat{g}}^{s,t,1} \geq 0 \qquad \forall (i,j)\in A, \forall \widehat{g}, \forall s, \forall t \qquad \psi_{i,j,\widehat{g}}^{s,t} \tag{67}$$

$$y_{i,j,1}^{d_2^s,t,2} \geq 0 \qquad \forall (i,j)\in A, \forall s, \forall t \qquad \dot{\psi}_{i,j}^{s,t} \tag{68}$$

$$x_{i,j,\widehat{g}}^{s,t} \geq 0 \qquad \forall (i,j)\in A, \forall \widehat{g}, \forall s, \forall t \qquad \ddot{\psi}_{i,j,\widehat{g}}^{s,t} \tag{69}$$

We write the first order conditions or KKT conditions for this problem. Since Z_L is a function of $x_{i,j,\widehat{g}}^{s,t}$, $y_{i,j,\widehat{g}}^{s,t,1}$, and $y_{i,j,1}^{d_2^s,t,2}$, hence, we need to write the KKT conditions based on each of these variables.

One. $\boldsymbol{x_{i,j,\widehat{g}}^{s,t}}$

Based on $x_{i,j,\widehat{g}}^{s,t}$, we can classify each $(i,j)\in A$ to the regular links ($\forall(i,j)\in(A-A^D)$) and the dummy links ($\forall(k,d_1^s)\in A^D$):

- $\forall(\boldsymbol{i},\boldsymbol{j}) \in (\boldsymbol{A}-\boldsymbol{A^D}), \forall \overbrace{g}, \forall \boldsymbol{s}, \forall \boldsymbol{t}$**:**

$$\frac{\partial\left(\sum_{t\in T}\sum_{(i,j)\in A}\int_0^{v_{i,j}^t}\sigma_{i,j}^t(\omega)d\omega\right)}{\partial x_{i,j,\overbrace{g}}^{s,t}} - \pi_{i,\overbrace{g}}^{s,t}\cdot\left(\frac{\partial\left(\sum_{j:(j,i)\in A}x_{j,i,\overbrace{g}}^{s,t} - \sum_{j:(i,j)\in A}x_{i,j,\overbrace{g}}^{s,t} - b_{i,\overbrace{g}}^{s,t}\right)}{\partial x_{i,j,\overbrace{g}}^{s,t}}\right)$$

$$-\pi_{j,\overbrace{g}}^{s,t}\cdot\left(\frac{\partial\left(\sum_{j':(j',j)\in A}x_{j',j,\overbrace{g}}^{s,t} - \sum_{j':(j,j')\in A}x_{j,j',\overbrace{g}}^{s,t} - b_{j,\overbrace{g}}^{s,t}\right)}{\partial x_{i,j,\overbrace{g}}^{s,t}}\right) - \ddot{\psi}_{i,j,\overbrace{g}}^{s,t} = 0$$

$$=> \ \sigma_{i,j}^t\left(v_{i,j}^t\right) - \pi_{i,\overbrace{g}}^{s,t} + \pi_{j,\overbrace{g}}^{s,t} - \ddot{\psi}_{i,j,\overbrace{g}}^{s,t} = 0$$

We also have $x_{i,j,\overbrace{g}}^{s,t}\cdot\ddot{\psi}_{i,j,\overbrace{g}}^{s,t} = 0$. Hence, we will have:

$$x_{i,j,\overbrace{g}}^{s,t}\cdot(\sigma_{i,j}^t\left(v_{i,j}^t\right) - \pi_{i,\overbrace{g}}^{s,t} + \pi_{j,\overbrace{g}}^{s,t}) = 0 \qquad \forall(i,j) \in (A-A^D), \forall\overbrace{g}, \forall s, \forall t \tag{70}$$

- $\forall(\boldsymbol{k}, \boldsymbol{d_1^s}) \in \boldsymbol{A^D}, \forall \boldsymbol{t}$**:**

$$\frac{\partial\left(\sum_{t\in T}\sum_{(i,j)\in A}\int_0^{v_{i,j}^t}\sigma_{i,j}^t(\omega)d\omega\right)}{\partial x_{k,d_1^s,1}^{s,t}} - \pi_{i,\overbrace{g}}^{s,t}\cdot\left(\frac{\partial\left(\sum_{j:(j,i)\in A}x_{j,i,\overbrace{g}}^{s,t} - \sum_{j:(i,j)\in A}x_{i,j,\overbrace{g}}^{s,t} - b_{i,\overbrace{g}}^{s,t}\right)}{\partial x_{k,d_1^s,1}^{s,t}}\right)$$

$$-\pi_{j,\overbrace{g}}^{s,t}\cdot\left(\frac{\partial\left(\sum_{j':(j',j)\in A}x_{j',j,\overbrace{g}}^{s,t} - \sum_{j':(j,j')\in A}x_{j,j',\overbrace{g}}^{s,t} - b_{j,\overbrace{g}}^{s,t}\right)}{\partial x_{k,d_1^s,1}^{s,t}}\right)$$

$$-\rho_k^t\cdot\left(\frac{Q\,{}_k^t\cdot\gamma_k^t - \sum_{s\in S}x_{k,d_1^s,1}^{s,t} - \frac{1}{\aleph}\cdot\sum_{s\in S}y_{k,d_2^s,1}^{d_2^s,t,2}}{\partial x_{k,d_1^s,1}^{s,t}}\right) - \ddot{\psi}_{k,d_1^s,1}^{s,t} = 0$$

- $\sigma_{k,d_1^s}^t\left(x_{k,d_1^s,1}^{s,t}\right) - \pi_{k,1}^{s,t} + \pi_{d_1^s,1}^{s,t} + \rho_k^t - \ddot{\psi}_{k,d_1^s,1}^{s,t} = 0$

Since $x_{k,d_1^s,1}^{s,t}\cdot\ddot{\psi}_{k,d_1^s,1}^{s,t} = 0$, hence, we will have:

$x_{k,d_1^s,1}^{s,t}\cdot(\sigma_{k,d_1^s}^t\left(x_{k,d_1^s,1}^{s,t}\right) - \pi_{k,1}^{s,t} + \pi_{d_1^s,1}^{s,t} + \rho_k^t) = 0.$

We also know that $\sigma_{k,d_1^s}^t\left(x_{k,d_1^s,1}^{s,t}\right) = \frac{1}{\theta_1^t}\Psi^t H_{k,1}^t + g_k^{s,t}$. Therefore,

$$x_{k,d_1^s,1}^{s,t}\cdot(\frac{1}{\theta_1^t}\Psi^t H_{k,1}^t + g_k^{s,t} - \pi_{k,1}^{s,t} + \pi_{d_1^s,1}^{s,t} + \rho_k^t) = 0 \qquad \forall(k,d_1^s) \in A^D, \forall t \tag{71}$$

Two. $\boldsymbol{y_{i,j,\widehat{g}}^{s,t,1}}$

This variable represents the traffic flow of AV travelers in each link in the first phase of AV travel.

$$\frac{\partial\left(\sum_{t\in T}\sum_{(i,j)\in A}\int_0^{v_{i,j}^t}\sigma_{i,j}^t(\omega)d\omega\right)}{\partial y_{i,j,\widehat{g}}^{s,t,1}}-\lambda_{i,\widehat{g}}^{s,t,1}\cdot\left(\frac{\partial\left(\sum_{j:(j,i)\in A}y_{j,i,\widehat{g}}^{s,t,1}-\sum_{j:(i,j)\in A}y_{i,j,\widehat{g}}^{s,t,1}-\bar{b}_{i,\widehat{g}}^{s,t}\right)}{\partial y_{i,j,\widehat{g}}^{s,t,1}}\right)$$

$$-\lambda_{j,\widehat{g}}^{s,t,1}\cdot\left(\frac{\partial\left(\sum_{j':(j',j)\in A}y_{j',j,\widehat{g}}^{s,t,1}-\sum_{j':(j,j')\in A}y_{j,j',\widehat{g}}^{s,t,1}-\bar{b}_{j,\widehat{g}}^{s,t}\right)}{\partial y_{j,j',\widehat{g}}^{s,t,1}}\right)-\psi_{i,j,\widehat{g}}^{s,t}=0$$

- $\sigma_{i,j}^t\left(v_{i,j}^t\right)-\lambda_{i,\widehat{g}}^{s,t,1}+\lambda_{j,\widehat{g}}^{s,t,1}-\psi_{i,j,\widehat{g}}^{s,t}=0$

Since $y_{i,j,\widehat{g}}^{s,t,1}\cdot\psi_{i,j,\widehat{g}}^{s,t}=0$, we will have:

$$y_{i,j,\widehat{g}}^{s,t,1}\cdot(\sigma_{i,j}^t\left(v_{i,j}^t\right)-\lambda_{i,\widehat{g}}^{s,t,1}+\lambda_{j,\widehat{g}}^{s,t,1})=0 \qquad \forall(i,j)\in(A-A^D),\forall\widehat{g},\forall s,\forall t \tag{72}$$

Three. $\boldsymbol{y_{i,j,1}^{d_2^s,t,2}}$

Finally, we need to write the first order conditions with regard to $y_{i,j,1}^{d_2^s,t,2}$ which is the traffic flow of AVs in the second phase of their travel. Similar to (1), we can classify each $(i,j)\in A$ to the regular links ($\forall(i,j)\in(A-A^D)$) and the dummy links ($\forall(k,d_2^s)\in A^D$):

- $\boldsymbol{\forall(i,j)\in(A-A^D),\forall s,\forall t}$**:**

$$\frac{\partial\left(\sum_{t\in T}\sum_{(i,j)\in A}\int_0^{v_{i,j}^t}\sigma_{i,j}^t(\omega)d\omega\right)}{\partial y_{i,j,1}^{d_2^s,t,2}}-\lambda_{i,1}^{d_2^s,t,2}\cdot\left(\frac{\partial\left(\sum_{j:(j,i)\in A}y_{j,i,1}^{d_2^s,t,2}-\sum_{j:(i,j)\in A}y_{i,j,1}^{d_2^s,t,2}-\bar{\bar{b}}_i^{d_2^s,t}\right)}{\partial y_{i,j,1}^{d_2^s,t,2}}\right)$$

$$-\lambda_{j,1}^{d_2^s,t,2}\cdot\left(\frac{\partial\left(\sum_{j':(j',j)\in A}y_{j',j,1}^{d_2^s,t,2}-\sum_{j':(j,j')\in A}y_{j,j',1}^{d_2^s,t,2}-\bar{\bar{b}}_i^{d_2^s,t}\right)}{\partial y_{i,j,1}^{d_2^s,t,2}}\right)-\dot{\psi}_{i,j}^{d_2^s,t}=0$$

$$\Rightarrow \qquad \sigma_{i,j}^t\left(v_{i,j}^t\right)-\lambda_{i,1}^{d_2^s,t,2}+\lambda_{j,1}^{d_2^s,t,2}-\dot{\psi}_{i,j}^{d_2^s,t}=0$$

Since $y_{i,j,1}^{d_2^s,t,2}\cdot\dot{\psi}_{i,j}^{d_2^s,t}=0$, we will have:

$$y_{i,j,1}^{d_2^s,t,2}\cdot(\sigma_{i,j}^t\left(v_{i,j}^t\right)-\lambda_{i,1}^{d_2^s,t,2}+\lambda_{j,1}^{d_2^s,t,2})=0 \qquad \forall(i,j)\in(A-A^D),\forall s,\forall t \tag{73}$$

- $\forall(\boldsymbol{k}, \boldsymbol{d_2^s}) \in \boldsymbol{A^D}, \forall \boldsymbol{t}$:

$$\frac{\partial\left(\sum_{t\in T}\sum_{(i,j)\in A}\int_0^{v_{i,j}^t}\sigma_{i,j}^t(\omega)d\omega\right)}{\partial y_{k,d_2^s,1}^{d_2^s,t,2}} - \lambda_{k,1}^{d_2^s,t,2}\cdot\left(\frac{\partial\left(\sum_{j:(j,i)\in A}y_{j,i,1}^{d_2^s,t,2} - \sum_{j:(i,j)\in A}y_{i,j,1}^{d_2^s,t,2} - \bar{\bar{b}}_i^{d_2^s,t}\right)}{\partial y_{k,d_2^s,1}^{d_2^s,t,2}}\right)$$

$$-\lambda_{d_2^s,1}^{d_2^s,t,2}\cdot\left(\frac{\partial\left(\sum_{j':(j',j)\in A}y_{j',j,1}^{d_2^s,t,2} - \sum_{j':(j,j')\in A}y_{j,j',1}^{d_2^s,t,2} - \bar{\bar{b}}_i^{d_2^s,t}\right)}{\partial y_{k,d_2^s,1}^{d_2^s,t,2}}\right)$$

$$-\rho_k^t\cdot\left(\frac{Q_{\ k}^{\ t}\cdot\gamma_k^t - \sum_{s\in S}x_{k,d_1^s,1}^{s,t} - \frac{1}{\aleph}\cdot\sum_{s\in S}y_{k,d_2^s,1}^{d_2^s,t,2}}{\partial y_{k,d_2^s,1}^{d_2^s,t,2}}\right) - \dot{\psi}_{k,d_2^s}^{d_2^s,t} = 0$$

- $\sigma_{k,d_2^s}^t\left(y_{k,d_2^s,1}^{d_2^s,t,2}\right) - \lambda_{k,1}^{d_2^s,t,2} + \lambda_{d_2^s,1}^{d_2^s,t,2} + \frac{1}{\aleph}\cdot\rho_k^t - \dot{\psi}_{k,d_2^s}^{d_2^s,t} = 0$

Since $y_{k,d_2^s,1}^{d_2^s,t,2}\cdot\dot{\psi}_{k,d_2^s}^{d_2^s,t} = 0$, hence, we will have:

$y_{k,d_2^s,1}^{d_2^s,t,2}\cdot(\sigma_{k,d_2^s}^t\left(y_{k,d_2^s,1}^{d_2^s,t,2}\right) - \lambda_{k,1}^{d_2^s,t,2} + \lambda_{d_2^s,1}^{d_2^s,t,2} + \frac{1}{\aleph}\cdot\rho_k^t) = 0.$

We also know that $\sigma_{k,d_2^s}^t\left(y_{k,d_2^s,1}^{d_2^s,t,2}\right) = \bar{\theta}\frac{1}{\theta_2^t}\Psi^t H_{k,2}^t$. Therefore,

$$y_{k,d_2^s,1}^{d_2^s,t,2}\cdot(\bar{\theta}\frac{1}{\theta_2^t}\Psi^t H_{k,2}^t - \lambda_{k,1}^{d_2^s,t,2} + \lambda_{d_2^s,1}^{d_2^s,t,2} + \frac{1}{\aleph}\cdot\rho_k^t) = 0 \qquad \forall(k,d_2^s)\in A^D,\forall t \tag{74}$$

We also need to write the complementarity constraint for the inequality constraint which is:

$$\left(Q_{\ k}^{\ t}\cdot\gamma_k^t - \sum_{s\in S}x_{k,d_1^s,1}^{s,t} - \frac{1}{\aleph}\cdot\sum_{s\in S}y_{k,d_2^s,1}^{d_2^s,t,2}\right)\cdot\rho_k^t = 0 \qquad \forall k,\forall t \tag{75}$$

This model ((62)-(75)) is same as the lower-level model presented in chapter 3 of this thesis.■