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16. Abstract

There is a need to optimally allocate curb space-one of the scarcest resources in urban areas-to the different and growing needs of passenger and freight transport. Although there are plenty of linear miles of curbside space in every city, the growing adoption of ride-hailing services and the rise of e-commerce with its residential deliveries, and the increased number of micro-mobility services, have increased pressure on the already saturated transportation system. Traditional curbside planning strategies have relied on land-use based demand estimates to allocate access priority to the curb (e.g., pedestrian and transit for residential areas, commercial vehicles for commercial and industrial zones). In some locales, new guidelines provide ideas on flexible curbside management, but lack the systems to gather and analyze the data, and optimally and dynamically allocate the space to the different users and needs. This study conducted a comprehensive literature review on several topics related to curb space management, discussing various users (e.g., pedestrians, bicycles, transit, taxis, and commercial freight vehicles), summarizing different experiences, and focusing the discussion on Complete Street strategies. Moreover, the authors reviewed the academic literature on curbside and parking data collection, and simulation and optimization techniques. Considering a case study around the downtown area in San Francisco, the authors evaluated the performance of the system with respect to a number of parking behavior scenarios. In doing so, the authors developed a parking simulation in SUMO following a set of parking behaviors (e.g., parking search, parking with off-street parking information availability, double-parking). These scenarios were tested in three different (land use-based) sub-study areas representing residential, commercial and mixed-use.

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NCST

Fighting for Curb Space: Parking, Ride-Hailing, Urban Freight Deliveries, and Other Users

A National Center for Sustainable Transportation Research Report

June 2021

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EXECUTIVE SUMMARY

In urban environments there are several users of curb space, each with competing demands. Curb space seeks to accomplish the six main functions of public right-of-way, defined as: mobility, access for people, access for commerce, activation, greening and storage. However, with a limited supply of curb space, users are forced to spend time searching through city streets for parking, leading to traffic congestion and excess emissions. To manage curb space effectively, cities must accommodate the needs of pedestrians, public transit, passenger cars, and everything in between. This report discusses the competing demands for curb space, and the policies and strategies that have been implemented to manage this limited supply. Specifically, this study examined, for a sample of selected cities and guidelines, how curb space is prioritized, and the specific strategies implemented to make each component of the transportation system work more effectively. Several management strategies that have been implemented nationwide include parking prioritization, demand-based parking, flex zones, transit prioritization, holistic planning, and Complete Streets. Overall, the literature on curbside management has concentrated on:

- Bicycles. Analyses have been conducted to identify the curb impacts of different bikeway classes, or the need for bicycle and shared mobility storage devices (Mitman et al., 2018).
- Transit. Studies and guidelines concentrate on transit lanes, bus queue jump lanes, bus bulbs/boarding islands, commuter shuttles and private transit, and automated enforcement of transit spaces (Roe and Toocheck, 2017; Mitman et al., 2018).
- Taxis, shuttles, and ride-hailing. There have been efforts to develop management strategies to change user behavior at different locations, e.g., large traffic generators such as airports and performance/sport venues. Studies and guidelines have also identified spatial and temporal-based changes in curb-allocation.
- Freight parking. Addressed through pricing, designated on-street, and off-street loading/unloading areas, or changing the location of on-street facilities to streets with lower traffic volumes.
- Parking availability to reduce ‘cruising’ for parking in downtown areas, as well as to mitigate other impacts on congestion and safety. Assigning curb space to parking dynamically according to time, price, and demand can allow parking availability when needed.
- Cars, especially when used as the main mode of transit, take up a great deal of space. Providing parking for all vehicles in a car-heavy environment compromises the space available to pedestrians, cyclists, transit, ride-hailing services, and freight. There are several strategies explored to maximize parking availability to reduce the amount of time cars must spend driving through cities searching for parking, including demand-

based parking, time limits, time-of-day restrictions, reduced occupancy targets, inclusions of off-street options, and priority parking programs.

Among the various guidelines reviewed, a recent important development is Complete Streets. A Complete Streets approach seeks to prioritize safety and diverse uses, and to consider the implementation of unique strategies to promote their successful integration into the urban transportation network.

Additionally, the literature includes studies related to:

- Curbside activity data collection;
- Curb demand modeling and forecasting;
- Curb and parking supply simulation and optimization;
- Evaluation of the energy and emissions associated with curbside management;
- Traffic and safety impacts of curbside demand; and,
- Governance, enforcement, and compliance.

Finally, concentrating on parking availability, ride-hailing and freight curb access demand, this study develops a simulation to examine the associated traffic impacts of these forms of curb demand using the SUMO (Simulation of Urban Mobility) software within the Traffic Control Interface (TraCI) package in Python. Explicitly, the simulation considers several scenarios for parking spaces for ride-hailing and loading-unloading areas, double-parking, varying parking time limits, and real-time off-street parking information availability. These scenarios are compared to a “business as usual” scenario in which vehicles of all types search for available parking. The study analyzed these scenarios for three study areas in San Francisco: commercial, residential, and mixed use.

1. Introduction

Passenger and freight demand have always competed for access to the curb. Traditionally, the space has been allocated to private vehicle parking, pick-up/drop-off locations, public transit stations, commercial vehicle parking, loading/unloading or staging areas, and other uses. Today, additional demand in the form of bike lanes, bus lanes, loading bays, car and bike-sharing services, and increasing needs for picking-up/dropping-off passengers and urban deliveries, among other uses, have increased the complexity of allocating this limited asset in urban environments.

Parking shortages, or the inadequate management of curb space, can contribute to negative transport externalities including congestion and increased environmental emissions due to cruising times and traveled distances. Lack of curb access can: foster double or triple parking, increasing conflicts between rights-of-way or between users; create unsafe conditions for the various road users; result in traffic infractions; and decrease the competitiveness of a city by increasing the cost of doing business. Many jurisdictions have developed policies to contend with parking management issues, and others have enforced parking management in their travel demand management strategies. Cruising, for instance, can have significant negative effects (King, 2010; Van Ommeren et al., 2012). Empirical analyses show that average cruising (parking search) times can range from 3.5 to 14 minutes, and can contribute 8% to 74% to traffic (Shoup, 2006). Lack of curb access could also increase the cruising of ride-hailing services when picking-up or dropping-off passengers, and the blocking of travel lanes. Strategies based on curb/parking pricing implemented to manage curb access have shown improvements in system efficiency and reductions in cruising (Millard-Ball et al., 2014). In San Francisco, the SFpark program showed reductions of 15% in search times, and 12% in parking distance (Alemi et al., 2018).

Although the ride-hailing process is similar to the traditional taxi, ride-hailing services have created a surge in curb demand. As a reference, a few years ago, taxis represented around 1% of the vehicle trips in San Francisco, yet ride-hailing trips are 15% of the total today (Wirschafter, 2018). This has prompted the city to work with service providers to try to address the issue (Fitzgerald, 2017a; 2017b).

The surge of ride-hailing trips is happening at the same time that e-commerce has significantly increased residential deliveries, with delivery vehicles also requiring access to the curb (Wang and Zhou, 2015). In terms of commercial freight parking, the problems have existed before the surge in residential deliveries. For example, Jaller et al. (2013a) analyzed the relationship between parking demand and availability. The empirical work showed that in Manhattan, about 25% of Zip codes would have a commercial parking shortage during peak demand periods even if the city allocated all curb linear distance for commercial vehicle parking. Other studies have shown the importance of developing freight parking policies (Nourinejad et al., 2014b; Marcucci et al., 2015a).

As cities continue to grow, curb space becomes an increasingly valuable commodity, thus, adequate curb management is critical for an efficient flow of people and goods. Moreover, transportation agencies must plan and develop strategies to improve system efficiency and sustainability (Marsden et al., 2020), though there have been reported challenges in the management process (Butrina et al., 2020). Agencies have tried structural reorganization (Karlin-Resnick et al., 2018), curb management pilot projects (Dey et al., 2017), and stakeholder education (Dey et al., 2019) to effectively manage curb space. However, there is limited empirical data or analyses on the combined curb space requirements due to the different transportation demands to develop management policies or strategies. Additionally, must analyses have been done by different agencies based on their particular needs/demands; thus, there are no specific studies that have evaluated the impacts from the various demands under the same modeling conditions. And, more importantly, regardless of strategy and across nearly all types of settings, enforcement (National Association of City Transportation Officials and Global Designing Cities Initiative, 2016) has been a major common problem. To provide additional insights into parking, loading and unloading management issues, this study conducts a review of the research and practice in curb and parking demand management. Additionally, the report discusses guidelines and strategies implemented in a sample of cities; provides an overview of various simulation and modeling tools available in the literature; and develops a simulation model to evaluate the performance of different parking scenarios and behaviors. For the simulation model, the research team concentrated on a study area in San Francisco with commercial, residential and mixed land use areas. The team combined data from empirically estimated vehicle demand using trip generation models for freight demand, and other data resulting from the Metropolitan Transportation Council Activity Based Travel Demand model (MTC-ABM) for the San Francisco Bay area. In doing so, the team modeled the MTC-ABM outputs using an agent-based model (MATsim) and microscopic simulation tool (SUMO) for a study area.

Simulation of Urban Mobility (SUMO) software is often used to simulate traffic and evaluate different traffic control methods. However, some travel behavior in SUMO is not completely reflective of real-life behavior, such as looking for brief stopping spaces or moving during serious congestion. To account for these variables, this study uses the "Traffic Control Interface" TraCI[1] package in Python, along with the SUMO interface to model vehicles circling around searching for parking, double-parking, and other behaviors. These behaviors include double parking permitted, double parking forbidden, off-street parking information known to drivers, and time limits for on-street parking. The research team developed the set of scenarios and evaluated their traffic performance for the three sub-study areas.

This report is organized as follows: Section II provides background on curb and parking management strategies implemented in a sample of cities; Strategies; Section III provides an overview of simulation and models from the literature; Section IV describes the simulation model developed in this project, the case study areas, the data used, and the simulated parking

[1] https://sumo.dlr.de/docs/TraCI.html

behaviors. Section V concentrates on the empirical analyses (simulation results) of parking and curb access demand, and the report ends with a summary and conclusions section (VI).

2. Background

Different users of curb space have different needs, thus, curb space allocation grows increasingly complex depending on user prioritization and local land use contexts. The literature on this topic has concentrated on the individual assessment of curbside access and parking needs for pedestrians, bicycles, transit, taxis and ride-hailing services, freight, and parking. Ride-hailing services such as Uber and Lyft have also surged in popularity, making scarce curb resources even more valuable.

Cities must balance competing demands with limited space. The Institute of Transportation Engineers defines the six main functions of public right-of-way to be mobility, access for people, access for commerce, activation, greening, and storage (Mitman et al., 2018). This definition includes the traditional uses of curb space and expands from those to capture such goals as providing adequate green space and space for vehicles at intersections. To ensure each of these goals is met, cities must utilize tools such as flex zones, layered network analyses, and living previews. This is crucial to ensuring whether a curbside management strategy can be implemented effectively.

Overall, cruising and searching for parking is a common trend, due to limited parking space and lack of available parking information. Cruising is especially problematic during peak hours in areas where available parking spaces are scarce. Vehicles searching for parking spaces not only slow down traffic and cause congestion, but also produce extra emissions (Coric and Gruteser, 2013). Examples of strategies to mitigate this issue include the SFpark pilot program in San Francisco, which helps drivers find open spaces quickly with real-time parking information. Information provided by the SFpark application facilitates finding parking spots f and congestion is reduced. San Francisco has also designated specific curb regions for pick-up and drop off-spots through their On-Street Shared Vehicle Parking Permit Program (Mitman et al., 2018). This provides space for users who are not using private automobiles, and reduces time spent searching for available curb space.

This section examines the demands of pedestrians, bicycles, transit, taxis and ride-hailing services, freight, and passenger vehicle parking. The review provides examples of different strategies used to accommodate such needs and users. Additionally, Appendix A provides an overview of Complete Streets designs which are a key strategy in curb management and allocation.

2.1. Pedestrian Use and Street Activation

Promoting pedestrian use over single passenger cars can improve urban vitality and allow the urban transit system to serve more people. Many thoroughfares emphasize the movement of vehicular traffic, but maintaining high quality transit, bicycle, and pedestrian facilities can maximize the efficiency of the overall transportation network. However, the needs of pedestrian travelers do not always coincide with the needs of other transportation options. People are more likely to travel on foot in areas that are efficient, walkable, and safe. Various strategies, although not comprehensively described here, can be implemented for pedestrian curb space prioritization to increase safety and promote walkable cities. Curb extensions are spaces that extend the sidewalk into the parking lane at intersections. These extensions make pedestrians more visible, shorten crossing distances, and slow vehicle turn movements. The widening of sidewalks can also increase pedestrian safety. Not only do wider sidewalks give more space for pedestrians to walk, but they also create more space between pedestrians and cars on the road.

Parklets can be implemented in urban environments to provide recreational spaces for pedestrians without compromising the efficiency of the transportation network. A "parklet" refers to an area where seating, patios, or other amenities are provided, without disrupting the sidewalk for mobility. This provides a destination for pedestrians to travel to, improves the vitality of streets, and give breaks to walkers. Pop-up parklets refer to small recreational spaces with flexible uses that arise in the middle of an urban environment. An example of a pop-up parklet in Texas is shown in Figure 1 (Downtown Austin Alliance, 2018). This parklet features amenities such as seating, bicycle parking, and vegetation for users to enjoy. And whilst, curb extensions and parklets are examples discussed here, there are other strategies and interventions that can help improve the safety and conditions for pedestrians.

Figure 1. Pop-Up Parklet in Austin, Texas (Austin Transportation Department, 2020)

Prioritizing pedestrians is appropriate where there is less need for vehicular mobility and a desire for person-based mobility, access for people, activation, and greening. Walking should be the desired mode of travel in several urban scenarios. Along transit destinations, pedestrian-friendly streets should be implemented to promote use of the transit system. Additionally, walkability is desired in areas such as parks or recreational facilities, where the goal is to have slower movement (San Francisco Planning Department, 2010). To preserve the natural environment in these areas, minimal automobile traffic is necessary. Additionally, in areas with narrow streets and short intervening distances, an increased shift to walking can greatly alleviate traffic. It is also important to recognize that contested curbs for pedestrian are mainly on places where walking is highest, though fostering a safe environment for pedestrians can bring about societal benefits. As part of the parking discussion is also relevant to mention the positive unintended consequence of on-street parking, which acts as a barrier between the curb and streets. Therefore, interventions should still consider this additional benefit of parking.

2.2. Bicycles

Increased bicycle usage can maximize the efficiency of transportation systems. Bicycles require much less infrastructure than automobiles and allow users to travel faster than on foot. Cyclists do have infrastructure and user requirements to maximize efficiency, including safe bike lanes, availability of parking, and connectivity to transit. Establishing biking as a primary mode to reduce vehicular demand requires updates to bicycle facilities, including (Mitman et al., 2018) protected bikeways, which are designated lanes for cyclists that are critical to the success of this mode of transportation. Selecting the appropriate type of biking infrastructure has to be consistent with the curb allocation, as different types of biking facilities can affect directly or indirectly curb use. Another important factor is storage, bicycle and shared mobility device storage, which entails providing parking spaces for bicycles.

Like prioritizing pedestrians, prioritizing bicycles is appropriate for areas where less automobile travel is desired. This includes parks and recreational facilities, and areas with narrow streets and short intervening distances. Bicycle prioritization is also vastly important near key transit stops. If there is bicycle infrastructure that is easily accessible via transit, usage of both modes of transportation is facilitated (San Francisco Planning Department, 2010). Cycling can allow travelers to get from a transit stop to their final destination much quicker than walking, in turn facilitating travel. Transit stops must be carefully designed for interactions between transit vehicles and bicycles where transit is present along bicycle priority corridors. In the last few years, shared mobility services have included bikesharing, with both dock-based systems, and dock-less or free floating. These services have highlighted the need to consider parking and storage space at the curb.

2.3. Transit

Increasing transit use plays a key role in discouraging single-occupancy vehicle travel and improving the efficiency of transportation networks. Transit priority refers to prioritizing transit in streets where high transit ridership is observed. To effectively increase transit ridership, strategies are often designed to prioritize transit on key corridors, including intersections and stops (Mitman et al., 2018). For transit to be successful, it must be efficient, easily accessible, frequent, and it must service desirable destinations. Several strategies have been implemented in cities to prioritize and improve transit. Transit lanes are often separated from other traffic by special pavement markings but not physical barricades. This allows transit to continue flowing, without being caught in the traffic of automobiles. Bus Queue Jumps are short transit lanes near signalized intersections, which allow buses to bypass vehicle congestion and drive quickly. In this system, buses will travel with the rest of traffic, but are able to bypass the rest of traffic during points of high congestion. Bus Bulbs and Bus Boarding Islands are unique curb spaces designed for bus stops. These allow easy entry and exit from the buses, increasing the safety and efficiency of the system. Commuter Shuttle and Private Transit Management is a strategy used to regulate commuter shuttles to improve safety and facilitate use for travelers.

Automated enforcement of transit space is a way of monitoring designated transit areas such as bus lanes to ensure that they are only used for transit. This improves the efficiency of the system by keeping unauthorized users out of transit spaces. Another important aspect to consider is the direct relationship between transit stops and curb access and use. This is because these spaces are reserved for transit and should not be used by other stakeholders.

Beyond the aforementioned strategies, there are other means of prioritizing transit. Clearing parking spaces at critical locations can improve transit efficiency by allowing more space at locations aligned with high ridership. Strategies such as adding a short right-turn pocket can allow transit to move quickly without being blocked by right-turning vehicles. Making room for transit is especially important during peak travel periods. While public transit may be heavily utilized during commute hours, it is often underutilized during other hours of the day, such as nighttime and weekends. Peak-period bus exclusive lanes can be used to extend the transit queue jump lane at peak times, and then convert it to loading or parking at non-peak times (Roe and Toocheck, 2017). The strategies used to improve transit ridership will have a direct impact on the curb, from directly requiring allocated space for parking and loading/unloading bays, to the ability to provide on-street parking.

2.4. Taxis, Shuttles, and Ride-Hailing

Ride-hailing services have lower prices and quicker response time characteristics when compared with traditional shuttles or taxis (Lu, 2018). Because of this, their ridership has greatly increased, causing substantial impacts on urban transportation. In San Francisco, for example, 40% of users are reported to have reduced their driving due to the adoption of ride-sourcing services (Better Streets San Francisco, 2011). The share of total trips made with Uber and Lyft on a typical weekday is reported to comprise 170,000 trips per day within the City of San Francisco. More specifically, the highest number of ride-hailing trips is on Fridays with over 222,500 trips; the lowest number is on Sundays with around 129,000 trips (Castiglione et al., 2016). A survey of ride-hailing users in California showed that, among surveyed people who frequently use ride-hailing services, the services replaced driving by 37 percent of trips, taxi use by 51 percent and transit use by 33 percent (Circella et al., 2018). All of these trips require access to the curb for the loading and unloading of passengers. Similarly, taxis and shuttles utilize curb space as loading and unloading zones. While they do not require curb space to be available for long periods of time, they do require openings to retrieve and drop-off passengers safely. With the surge in popularity of ride-hailing services such as Uber and Lyft, demand for this type of curb space has increased. Ensuring that there is adequate space for these services for pick-up and drop-off of passengers competes with other uses of curb space.

Access for loading and unloading activities is important for curbside management. These activities include passenger pickup and drop off activity, and freight loading and unloading activities. Identifying demand for passenger loading and unloading space is the first step for adequate planning of the curb, e.g., for passenger loading and unloading zones.

Parking for on-streetcar-sharing (ride-sharing, ride-hailing and other forms) has different needs than traditional passenger vehicle parking. Car-sharing can reduce parking demand, vehicle miles traveled, and auto emissions. Cities could choose to designate on-street spaces per block for the exclusive use of car-share, providing greater access to shared vehicles. In these designated car-share zones, for-hire vehicle companies and taxi drivers could safely conduct passenger pick-ups and drop-offs during peak hours (Los Angeles City Planning, 2016), allowing these drivers to exit the traffic lane (avoiding blocking other drivers) and pull over to the curb so that their passengers can have safe passage to the sidewalk. Outside of peak hours, these spaces could be converted back to regular parking spaces for consumer vehicles, or where needed, be designated as commercial delivery zones to prevent congestion caused by double-parked trucks.

Urban environments should accommodate taxis, shuttles, and ride-sharing in areas that are underserved by transit networks, including residential areas, where low density makes other forms of transit difficult. Such ride-sharing forms can be utilized to get users from a transit stop to their final destination without the same parking needs that single passenger cars would require. Ride-hailing services are also utilized in nighttime commercial and cultural activities within close proximity to a downtown area, where large groups are in attendance.

2.5. Freight

Freight systems use several different sizes of delivery vehicles, ranging from hand carts to large trucks, and depending on the most common vehicles used, curb space requirements can shift. The greatest priority for a freight network is the availability of loading and unloading zones near shipping destinations for deliveries, whether those destinations are commercial establishments or residences (National Association of City Transportation Officials, 2012). There are several strategies affecting curb access for freight vehicles. For example, freight zone pricing using paid permits controls the number of loading zones available at designated times while reducing the duration of occupancy. Charging delivery vehicles for deliveries made in peak-time will encourage off-peak deliveries, and off-peak deliveries reduce traffic and parking stress in peak hours. Staging zones for delivery vehicles designate waiting areas to access off-street loading and unloading zones. This is useful in high-demand building locations because it can help reduce double parking and trucks circling around the block. Toronto is currently evaluating a delivery vehicle staging strategy as part of its Curbside Management Strategy (Mitman et al., 2018). Another strategy is using smaller vehicles for last- mile deliveries. Last-mile deliveries via smaller, low-emission vehicles will reduce the conflicts of large vehicles competing over road space. Moving loading and access around the corner can also lessen impacts on the network. These access points can be moved to adjacent streets from the destination building with high-traffic volume (Mitman et al., 2018). Some delivery drivers prefer to park in one place and walk to their final destination. Freight loading zones can be moved out from the main street to relieve the pressure on transit stops, while still meeting the needs of delivery drivers (see Figure 2 for an example in New York City). Cities should also explore off-peak freight delivery incentives for busy areas.

Commercial loading zones can provide access for loading/unloading and reduce the double parking of delivery vehicles. Commercial loading zones should be applied in select locations along commercial corridors where on-street parking is scarce or where high volumes of deliveries currently occur. Loading zones should be consolidated at midblock locations if feasible, to avoid conflict with other vehicles near intersections.

Freight vehicles should be accommodated over other modes in environments where there are large demands for the loading and unloading of goods, including retail and commercial establishments, as well as locations where there are many industrial and manufacturing facilities that require frequent shipments. In transfer points for bulk equipment, and along truck and rail routes, freight should be prioritized as well. Additionally, freight is required in heavier demand in areas where the materials that must be shipped would become a nuisance or health hazard if stored on site. When freight cannot be prioritized at exact destinations, adjacent curb space should be allocated for freight as a compromise.

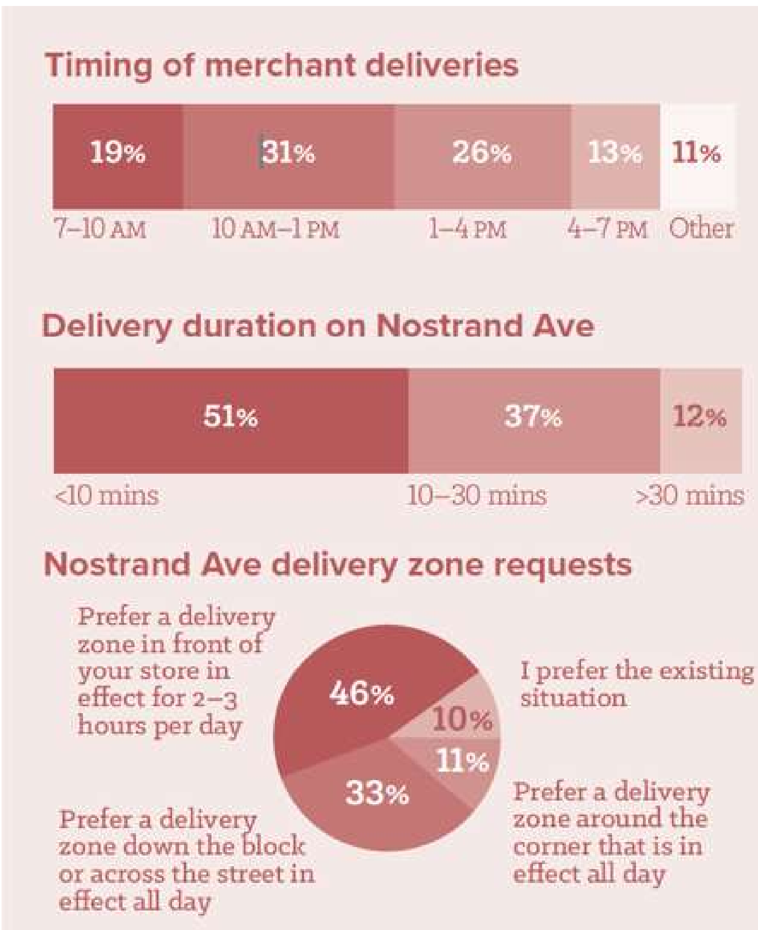


Figure 2. Time and Duration of Merchant Deliveries and Driver Preferences

2.6. Parking Availability

Parking availability is critical to reducing cruising for parking in downtown areas. Assigning curb space to parking dynamically according to time, price, and demand can allow parking availability when needed and reduce cruising traffic. Cars, especially when used as the main mode of transit, take up a great deal of space. Providing parking for all vehicles in a car-heavy environment compromises the space available to pedestrians, cyclists, transit, ride-hailing services, and freight. Thus, there are several strategies explored to maximize parking availability to reduce the amount of time cars spend driving through cities searching for parking. Demand-Based Pricing refers to adjusting paid parking rates according to demand. Sometimes parking rates can change dynamically by real-time demand information. By adjusting the parking rates during times of high demand, drivers are incentivized to explore other modes during these time periods. This cuts down on peak-hour demand, and allows the amount of required parking spaces to be minimized. Setting time limits such as allowing 10 to 15 minutes of occupancy, can reduce parking occupancy, giving space for the next vehicle and avoiding illegal parking. Also, meter rates can be changed over time, such as making the second 15 minutes more expensive than the first 15 minutes in busy areas (San Francisco Municipal Transportation Agency, 2017). Away from the busiest area, cheaper or longer-term parking needs are more easily accommodated. Demand-based pricing needs to be based on real-time occupancy data, and metered rates adjusted to respond to fluctuating parking demand over time.

Time limits prioritize short duration parking, which reduces the occupancy of parking space. Time-of-day restrictions can be used in areas with significant parking demand, balancing the needs of all users and using curb more efficiently and flexibly. With limits placed on how long users can park, they are likely to only utilize passenger cars for trips that are shorter. For those who would normally need a longer time to park, such as drivers commuting to work, parking becomes less readily available. This incentivizes the use of other modes of transportation, which are more efficient. Time-of-day restrictions limit parking during specific times of the day. This allows curb space to be used for other activities during certain time periods, while still allowing cars to park during other time periods.

Reduced Occupancy Target is another strategy for designing parking spaces. The general occupancy rate of a city's parking spaces should not be designed at 100%, but rather at 90% or lower depending on modals. By designing parking to meet 90% occupancy, there should always be sufficient parking spaces available somewhere in the system. Having a parking occupancy rate of 90% means the parking system is being adequately used, but also allows cars to find spots without having to spend large periods of time cruising (Mitman et al., 2018). Lower target occupancy rates should be designed for dedicated short-term parking or loading, reflecting a goal of keeping lanes clear rather than a goal of always using the curbside as intensively as possible.

Another strategy is inclusion of off-street options. Off-street parking should be considered to increase total parking spaces. In a given neighborhood or zone, to reduce non-resident parking and increase parking availability for residents, Priority Parking Programs can be implemented. Residential parking permits (RPP) and similar parking restriction programs can discourage specific areas as parking destinations.

Automated enforcement of curbside and transit lane regulations, such as camera capturing, can improve the efficiency of the entire street. Automated parking enforcement is effective against parking in transit lanes and double-parking. The lowest effective fine should be used for illegal parking, and higher fines should be used when needed. Automated enforcement is effective because it is consistent, predictable, and unbiased. Fines and payment instructions should be noted clearly and understandably for all people online. Procedures of enforcement should not subject people of color and people in lower-income neighborhoods to disproportionate enforcement (Roe and Toocheck, 2017).

2.7. Utilizing Curb Space as a Flex Zone

Curb space has varying potential uses, allowing it to be considered a flex zone. Flex zones refer to designating areas flexibly, or on a changeable basis, that do not have fixed uses on a roadway. There are three different types of flex zones to accommodate different functions. These different types occur depending on if the same place is used for multiple functions simultaneously, if the same place is used for different functions at different times, or if different spaces are used for multiple functions at the same time. Flex zones are an efficient way of using curb space according to demands for different locations and points in time. A layered network approach is designed to allow all users be served effectively with the appropriate priorities met along the roadway (Mitman et al., 2018). Transit stops, transit lanes, bikeways, bike share stations, commercial loading, pick-up/drop-off areas should all be considered and ranked as different priorities for industrial areas, residential areas and commercial or mixed-use areas. Figure 3 and Figure 4 show examples of potential types of flex use and flex zones.

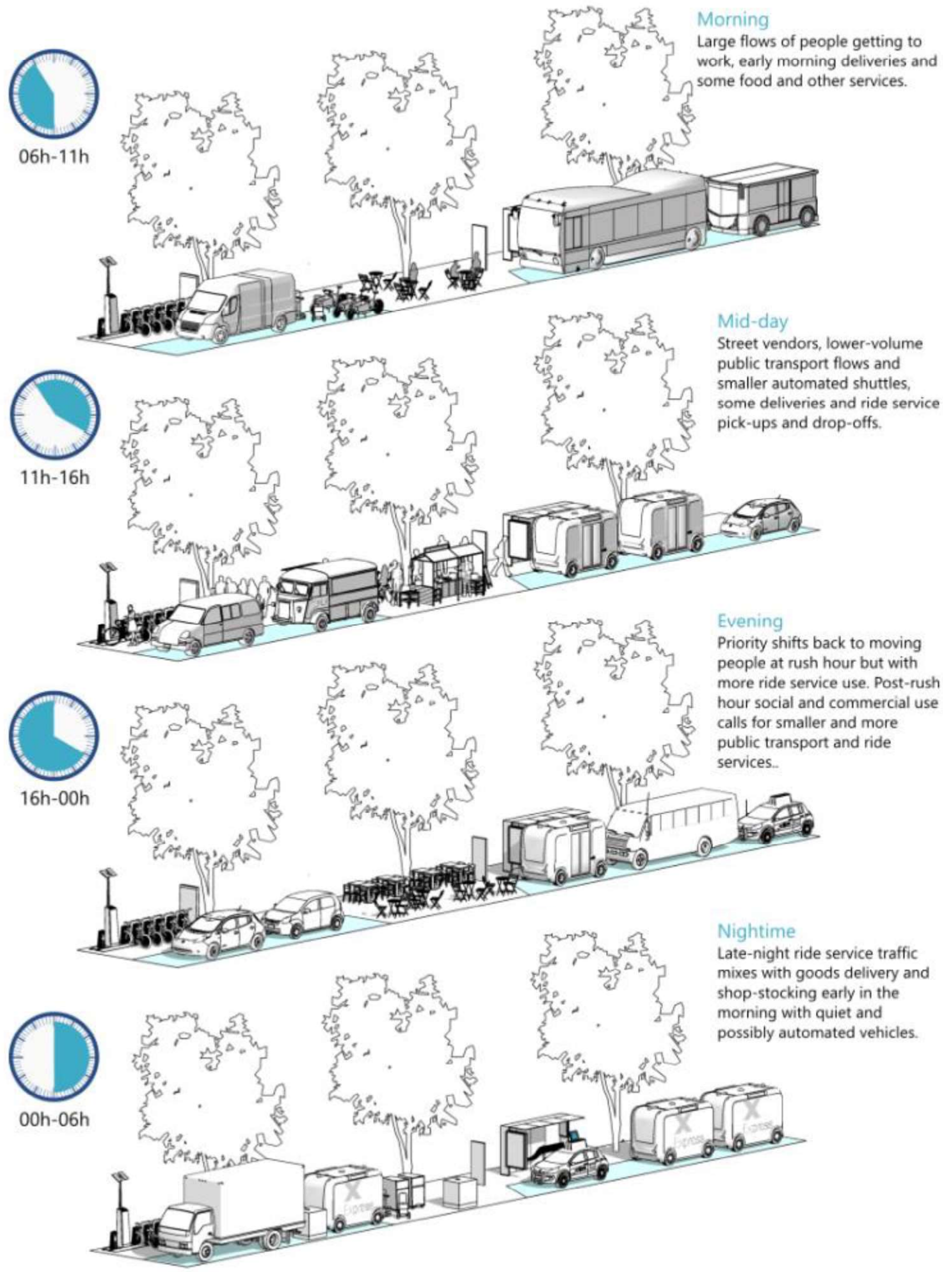


Figure 3. Curb Demands vs. Time of Day (International Transport Forum, 2017; National Association of City Transportation Officials, 2019)

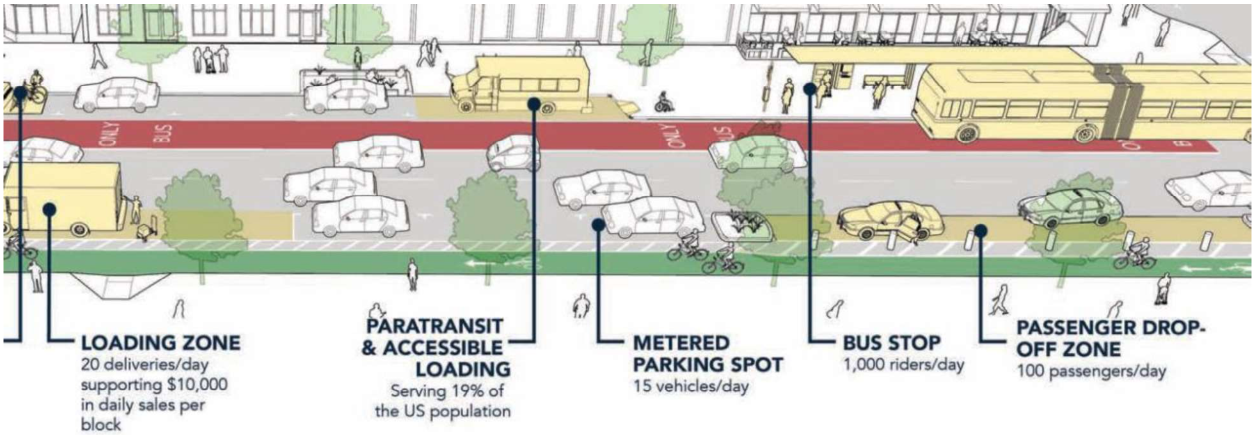


Figure 4. Examples of Various Flex Zone Uses (Roe and Toocheck, 2017)

2.8. Modal Priority

The travel mode that should be prioritized depends on the local context of land use and activity. Modal prioritization may change over time for some contexts. To accommodate varying needs, cities may choose to implement mixed-uses on main streets or at access points, with different modes prioritized depending on the location and associated demands. Table 1 shows an example of different priorities for the city of Seattle (Seattle Department of Transportation, 2018). Support for modal plan priorities is the most important factor in all areas, followed by access for commerce and pedestrians. Activation is implemented more in commercial and mixed used spaces, as it serves to offer social spaces for public interaction, such as food trucks and parklets. Greening seeks to enhance the aesthetics and environmental health of an area by providing vegetation, and storage seeks to provide space for storing vehicles or equipment. Mixed use access is suitable for streets providing direct access to nearby commercial, retail, or residential properties. These are typically minor roadways, where access for commerce, people and parking is of higher priority. Their primary purpose is to provide access to other nearby areas, so curb space allocated for greening, storage, and activation is moved to other nearby streets.

Table 1. City of Seattle Curbside Use Priority

Priority	Residential	Commercial & Mixed Use	Industrial
1	Support for Modal Plan Priorities		
2	Access for People	Access for Commerce	
3	Access for Commerce	Access for People	
4	Greening	Activation	Storage
5	Storage	Greening	Activation
6	Activation	Storage	Greening

2.9. Summary of Various Implemented Projects

Table 2 summarizes several different projects or strategies implemented in different cities. Some of the most used strategies include demand-based parking pricing, commuter shuttle and private transit management, and flex zones. Each of these projects were implemented to best accommodate varying users of curb space, to remediate congestion impacts, and to improve safety. It is also important to acknowledge that parking management has also received increased attention as a travel demand management strategy, though this dimension to curb and parking management was outside the scope of the study.

Table 2. Examples of Curb and Parking Management Implementations and Pilots

Project name	Benefits	Description
Vision Zero Action in San Francisco	Safety for all road users	Vision Zero is a citywide effort including protected bike lanes, building new traffic signals and pedestrian countdown signals and, making crosswalks more visible
Flex zone in Seattle	Enhance safety, movement efficiency, and access	Flex zone functions are prioritized based on land use
APP (GoDCgo)	Easier to park, reduce searching time, costs, and emissions	Parking in a load zone requires the purchase and display of a permit or pay-by-cell after parking. Freight demand and parking management
Downtown Austin Parking	More parking space	Off-street parking to provide more parking capacity
Demand-Responsive Parking in San Francisco (SFpark Pilot Program)	Increase the number of available metered parking spaces in peak-hours, and reduce demand	SFpark collected and distributed real-time information about available parking, reducing traffic stress and congestion. Demand-responsive pricing encourages drivers to park in underused areas and garages
PARK Smart Program in New York		Implemented parking rate changes. Set aside commercial space for deliveries
Penn Quarter/ Chinatown Parking Pricing Pilot	Easier to park	Parking price change with time(off-peak or peak)
Off-Hour Deliveries (OHD) Program in New York	Faster speed and lowered congestion reduced cost, fuel use, and illegal parking	Increase good deliveries between 7PM-6AM when there is less congestion, user volumes, and more parking space
On-Street Shared Vehicle Parking Permit Program	Reduce parkup /drop-off times making ride hailing more attractive, decreasing private vehicles	Painted curbs for pick-up and drop-off (PUDOs) spots. About 210 on-street spaces at 140 locations
Commuter Shuttle Program (San Francisco)	Reduce VMT and associated congestion, emission and cost, and encouraged active modes and transit	Up to 125 shuttle stop locations, including shared Muni zones and shuttle-only loading zones. Regulations for shuttle loading and unloading and increased safety
Private Transit Vehicle (PTV) permit program (San Francisco)	Reduce unsafe passenger loading, minimize travel on restricted streets, collect data	Regulation of private transit
Car-Free Living Program	Encouraging people to use transit and ride-share	Participants receive a $100 monthly transportation credit per apartment to use with Get around, Clipper and Uber
Dockless bike parking in Seattle	Encourage people to ride	Designated areas for dockless bike parking
Loop Link project in Chicago	More reliable bus services and safer	Dedicated bus lanes and limited stops at train-like stations
Bay Street Road Diet and Cycle-track	Reduce vehicle speed and enhance safety	Reducing vehicle speeds to promote other modes

Sources: (San Francisco Municipal Transportation Agency, 2009; City of New Haven, 2010; Better Streets San Francisco, 2011; National Association of City Transportation Officials, 2012; Caltrans, 2013; Santa Cruz County Regional Transportation Commission, 2013; Whitlock & Weinberger Transportation Inc., 2013; Authority, 2015; Los Angeles City Planning, 2016; Orange County Council of Governments, 2016; International Transport Forum, 2017; StreetPlans et al., 2017; Transportation, 2017; Authority, 2018; District Department of Transportation, 2018; Downtown Austin Alliance, 2018; Sacramento County, 2018; Seattle Department of Transportation, 2018; National Association of City Transportation Officials, 2019; North Carolina Department of Transportation, 2019; San Francisco Planning Department, 2019; Vision Zero SF, 2019; Alameda County Transportation Commission, 2020; goDCgo, 2020; New York City Department of Transportation, 2020)

3. Parking Demand Modeling and Forecasting

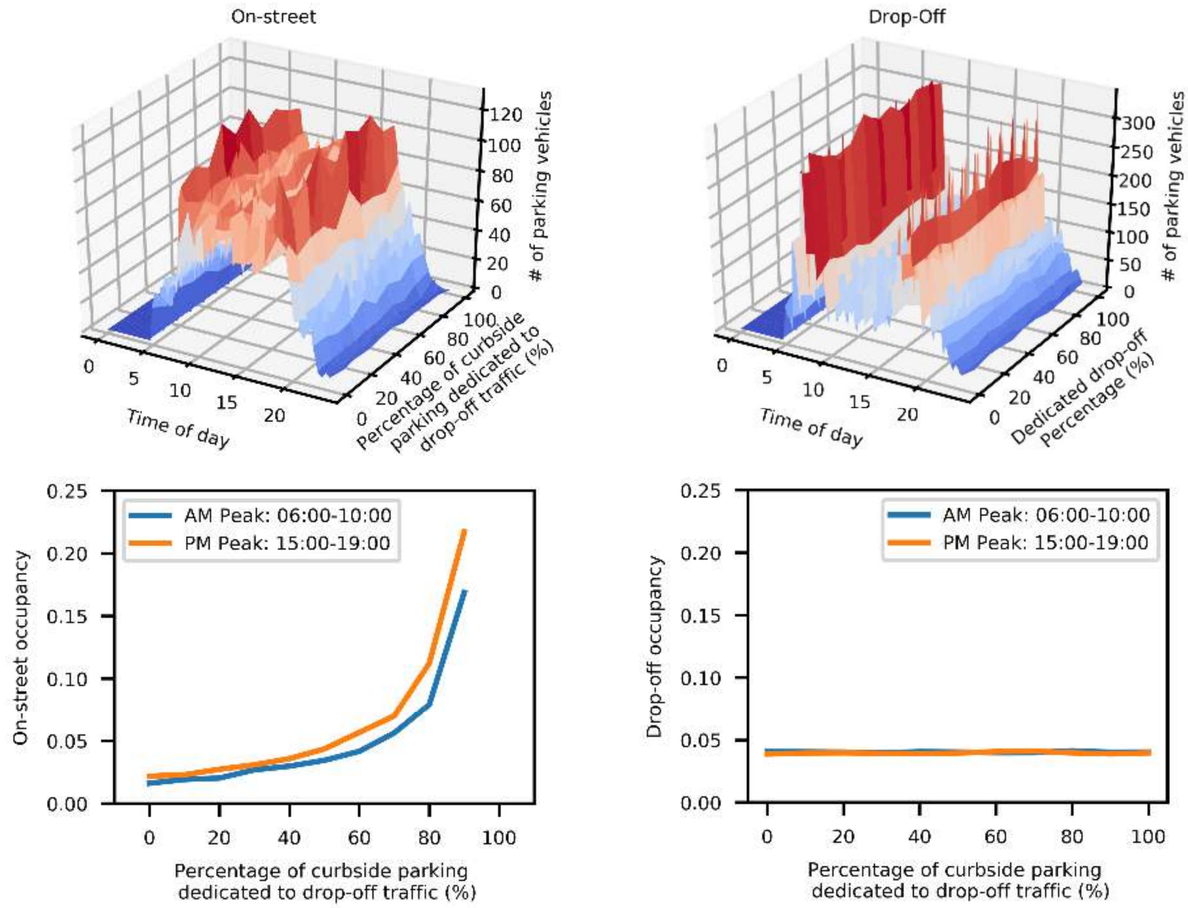
The curb demand modeling literature has focused mainly on the conventional use of curbside space for the on-street or off-street parking of passenger vehicles and trucks. There are only a handful of studies modeling the loading and unloading demands of ride-hailing services due to limited data. Similarly, cargo loading and unloading activities have been understudied, and existing empirical studies have relied on project-specific data collection efforts using surveys, vehicle counting, and parking utilization for aggregate or disaggregate analyses (Jaller et al., 2013a; Nourinejad et al., 2014a; Zou et al., 2016), or used GPS data to analyze the routes, parking durations, and searching times (Greaves and Figliozzi, 2008).

Some of these studies have demonstrated the use of machine learning techniques to analyze such data (Yang et al., 2014), with particular emphasis on the correct identification of delivery/pick-up vehicle stops (as opposed to traffic flow-related stops/idling). The literature also includes recent efforts to use crowdsourced data (vehicles as sensors) to estimate parking supply (Genc et al., 2013). Another branch of studies has focused on behavioral analyses using econometric techniques. For example, Marcucci et al. (2015b) developed choice models for the selection of parking policies and strategies, and e Silva and Alho (2017) analyzed parking issues using structural equations modeling.

Recently, the researcher team conducted a number of studies to analyze the impact of different strategies based on simulations of curbside demand. Specifically, the study developed a micro-simulation tool to assess the impacts of autonomous and connected vehicle pick-up and drop-off activities in traffic flow, and the evaluation of some curb management strategies. The tool used the Simulation of Urban Mobility (SUMO) open source and focused on specific areas in San Francisco. For the simulations, the team developed algorithms to simulate the idling and parking search behaviors, the use of PUDOs, real-time off-street parking information availability, time limits, and double-parking violation enforcement scenarios (see Figure 5 for examples of results). Similarly, when analyzing the impacts of PUDOs and infrastructure allocations, the team found significant system improvements between the PUDOs vs. on-street parking allocations (Chai et al., 2020).

Regarding the estimation of ride-hailing demand and the resulting curb access issues, there are only a handful of studies. For example, (Circella et al., 2018) developed discrete choice models for the adoption of on-demand ride services using various explanatory variables including socio-demographics, individual lifestyles, and built environment characteristic variables. They also developed models for the frequency of use of ride-hailing services in San Francisco. Other studies include the Ride-sources Street Index, which computes ride-sourcing trips originating from or attracted to one street, according to commercial density in that street (Ramsey and Bell, 2014; Lu, 2018). According to Castiglione et al. (2016), there were 170,000 trips of TNC in San Francisco, comprising 15% of all intra-San Francisco vehicle trips in 2016.

Additionally, the San Francisco Planning Department conducted a recent study to analyze the mode split in usage between automobiles, taxis, public transit, walking, and bicycling by time of day and land use type (Figure 6). This data is further broken down to show the differences between areas of high, medium, and low density. As shown in these charts, automobile use is the dominant mode of transportation in all regions, especially in areas of low density. Meanwhile, high density areas attract more users of transit, walking, and taxis.



a) On-street parking occupancy b) Drop-off parking occupancy

Figure 5. Parking occupancies from different types of traffic

Through the collected data, SFPD could be able to estimate passenger loading demand by using the mode split percentage of all person trips going to a particular site. Percentages differ according to land use and place type, as seen in Table 3. These passenger loading percentages are calculated using the planning department’s intercept survey data collection in Spring 2017.

Figure 6. Mode Split by Land Use and Location Type (San Francisco Planning Department, 2019)

3.1. Curbside Activity Data Collection and Impact Assessment

Much of the existing curbside data collection has focused on traditional approaches to the inventory and monitoring of on-street parking. These approaches include: the collection of parking administrative data (Kobus et al., 2013; Ottosson et al., 2013) by on-site traffic counting and space inventory; the use of vehicle tracking through expensive in-ground sensors (though different technologies have become less expensive); and through manually labelled video and time-lapse photos (Dey et al., 2017). Other approaches have used Global Position Systems (GPS) to track vehicle movements, especially for commercial deliveries (installed on trucks or vans), complemented with driver surveys or diaries (Jaller et al., 2013a; Zou et al., 2016). However, most of these data collection techniques are expensive, limiting the frequency and size of the samples, resulting in a systematic lack of knowledge about curbside use, especially in terms of what is needed to develop efficient management plans and actions to contend with changing needs and the advent of new mobility services and technologies such as ride-hailing services, micro-mobility, and e-commerce (residential) deliveries that use conventional freight vehicles, as well as other passenger-related modes (e.g., passenger cars, bicycles, autonomous mobile robots for crowd-shipping services). Additionally, nascent companies digitalizing curb spaces are only focusing on the supply side, and do not monitor the demand side of curb access.

Table 3. Curb Loading Type in San Francisco with Various Land Uses

Land Use	Geography	Number of Sites	Taxi/TNC%	Private Vehicle Drop-off (50% of HOV Passenger Mode)	Passenger Loading %
Office	Place Type 1	8	6.1%	1.2%	7.3%
	Place Type 2	7	11.0%	2.4%	13.4%
	Place Type 3	3	2.0%	5.1%	7.1%
Retail	Place Type 1	4	4.6%	0.9%	5.5%
	Place Type 2	10	1.4%	1.6%	3.0%
	Place Type 3	7	1.0%	4.2%	5.2%
Residential	Place Type 1	4	6.0%	2.8%	8.8%
	Place Type 2	9	3.5%	3.7%	7.2%
	Place Type 3	2	4.2%	2.7%	6.9%
Hotel	Place Type 1	4	19.6%	2.2%	21.8%
	Place Type 2	5	15.6%	4.1%	19.7%
	Place Type 3	2	7.5%	6.0%	13.5%

Note: Because survey respondents were not asked to specify if they were dropped off or simply part of a group arriving in single vehicle, the methodology assumed a 50 percent factor for HOV trips for purposes of loading analysis.

There are just a handful of studies analyzing curbside layouts and design impacts on traffic and safety. Some of these have focused on the specific use of the curb, considering bus stops (Jin et al., 2019), loading and unloading zones at airports (Passos et al., 2011; Harris et al., 2017), cruising for parking (Van Ommeren et al., 2012; Arnott and Rowse, 2013) and commercial loading and unloading zones. Consequently, there is a need for decision-support tools based on mathematical modeling and/or simulation that can capture mixed uses, dynamic patterns of demand, and that can evaluate the impacts of different layouts on curb performance.

Some recent efforts towards the evaluation and assessment of energy and environmental impacts from curbside activity include the concepts put forward in the curb productivity metric developed by Uber and Fehr & Peers (Smith et al., 2019), the Institute of Transportation Engineers (ITE) curbside management practitioners guide (Mitman et al., 2018), and the mobility energy productivity metric to quantify the number of opportunities (e.g., jobs, medical services, parks) that people can reach weighted by the time, energy and cost-efficiency developed by NREL and adopted by DOE.

3.2. Curb and Parking Supply Simulation and Optimization

There have been several studies addressing on-street parking supply based on travel demand using simulation and optimization tools. Some of these have implemented dynamic optimization (Qian and Rajagopal, 2014; Mackowski et al., 2015; Zheng and Geroliminis, 2016) or used game theory (He et al., 2015; Mackowski et al., 2015). (Arnott and Inci, 2006) developed a parking equilibrium model considering known hourly constant demand, which omits the dynamic nature of parking behavior. PARKAGENT developed by (Benenson et al., 2008), is a spatial agent-based model considering drivers' reactions to parking spaces, pricing, enforcement, and other drivers' behaviors using rules. (Waraich and Axhausen, 2012) also experimented with an agent-based model to analyze cruising for parking considering three cases: driving to an activity, searching for a parking space, and leaving the activity. SUSTAPARK is a spatio-temporal simulation tool based on a cellular automation network using utility functions for parking choices (Dieussaert et al., 2009). In terms of freight, (Nourinejad et al., 2014a) developed dynamic and microscopic parking models with distinct behaviors between passenger and freight vehicles. Table 4 summarizes the various models in terms of inputs and outputs.

Although there are already some existing models in the literature, they mostly assume parking demand as deterministic or static, which under the current needs of the system (e.g., ride-hailing, micromobility, and e-commerce deliveries) is too strong of an assumption for the optimal allocation of parking space. Very few works, to date, directly consider demand uncertainty via stochastic programming approaches. Recent examples for stochastic parking optimization have been proposed to identify optimal parking solutions for shared fleets (Xu et al., 2017) and private autonomous vehicles (Wang et al., 2019), though for hypothetical case studies. (Wang et al., 2019) developed mixed integer programming to optimize the spatial configuration of parking to minimize the economic opportunity costs of parking spaces while controlling the extra VMT generated by private automated vehicles (Wang et al., 2019) and optimizing daily travel routines for PAV households (Zhang et al., 2018). There are important gaps to be addressed in terms of the incorporation of uncertainties in the adoption of new mobility services for passengers and goods, the development of solution algorithms and methodologies that can take advantage of real-time data, and the ability to efficiently solve large problem instances for long-term planning capabilities.

Table 4. Examples of simulation and optimization models for parking

Model	Input	Output
Parking Equilibrium Model (PEM)	Multimodal supply model Parking demand by trip purpose, Nest Logit Model	Parking time
	Demand level assumptions with respect to supply levels	New demand equilibrium in transit and cars
	Multi-layer network supply model, demand is assumed by parking saturation value	VMT
PARKAGENT (ArcGIS)	Group of drivers with different behavior	Life-path of every model driver
	Theoretical research	Cruising time & car distribution
	MATsim	Parking route
	Attraction coefficients for different trip purposes based on building characteristics	Number of on-street parking spots
Parking Search Behavior Model	Scenarios for the number of searching agents	Number of on-street parking spots
SUSTAPARK	Microscopic simulation using network data per zone, O-D matrix, and results from a four-step macroscopic traffic assignment (to determine flow volumes for each turn in the network)	Selected parking spaces
A dynamic, microscopic parking model for freight (TRAMOS)	Truck counts	Time corresponding to different scenarios
PM peak hour parking simulation model	Simplified 60,000 agents model for Berlin	Parking demand and parking time
A simulation model with car sharing including parking search behavior	Truck and passenger vehicle demand matrices, parking choice model, simulation model	Dwell time

Sources: (Arnott and Inci, 2006; Benenson et al., 2008; Dieussaert et al., 2009; Waraich and Axhausen, 2012; Nourinejad et al., 2014a; Bischoff and Nagel, 2017; International Transport Forum, 2018; Lu, 2018)

4. Simulating Curb and Parking Demand

To simulate curb and parking demand in San Francisco, the team combined data from empirically estimated commercial vehicle demand using trip generation models, and other data from the Metropolitan Transportation Council Activity Based Travel Demand model (MTC-ABM).

Overall, the San Francisco Bay area is one of the largest economies in the United States and is home to over 7 million residents. According to the County Business Pattern dataset (U.S. Census Bureau, 2011), there are a total of 183,104 establishments located in the nine-counties, which provide more than 3.2 million job opportunities. In San Francisco, during peak-hours, both automobile and transit speeds can reach as low as 10 miles per hour (Metropolitan Transportation Commission, 2011), particularly in the Downtown and Central Business Districts (CBD). For a number of transportation demand projects, the research team has used the MTC-ABM model. According to the model, the Bay Area generates about 24 million total daily trips, out of which single-occupancy vehicles are responsible for 48%, 36% by shared ride (with another household member), 9.76% by walking, 1.02% by bike, and 4.78% by transit. In terms of freight trips, approximately 378,000 truck trips originate or end in San Francisco County. In this project, the team concentrated on a sub-area of San Francisco (e.g., Downtown, south Market Street). The team analyzed the modeling outputs from MTC-ABM to gather information about traffic conditions (travel speeds, congestion levels) and origins and destinations in the study area. Moreover, the team gathered the generated data for the daily activities of the individuals inside this area to use as inputs in the agent and activity modeling effort. Additionally, the team used freight trip generation models to estimate the commercial vehicle curb demand.

For the agent-based modeling, the team used MATsim, which is a software capable of using the travel activity patterns resulting from the MTC-ABM and efficiently conducting dynamic traffic assignment and simulation. The team have developed integrated the outputs from MATsim and MTC. MATsim offers advantages over the MTC-ABM results, as the latter generates link-based outputs and aggregates them over hourly periods. Instead, MATsim is able to simulate travel activity minute by minute, which allows a better understanding of the dynamics of travel demand on curb access. The MATsim simulation provided additional details in terms of potential curb space demand. Finally, the team used SUMO for the microscopic analyses. The team already had test beds calibrated for San Francisco for both MATsim and MTC-ABM.

Simulation of Urban Mobility (SUMO) software offers the ability to model person-based intermodal traffic simulation. This reproduces the individual person undertaking a series of trips in different modes, e.g., passenger vehicle and walking. The model is able to simulate the interaction between the individuals and vehicles in time and space. However, some travel behavior in SUMO is not completely reflective of real-life behavior, such as looking for brief stopping spaces or moving during serious congestion. To account for these variables, this study uses the TraCI package in Python, along with the SUMO interface to model vehicles circling around searching for parking, double parking, and other behaviors. These behaviors include double-parking permitted, double-parking forbidden, off-street parking information known to drivers, and time limits for on-street parking. The reader is referred to http://sumo.dlr.de/wiki/Simulation/ParkingArea for additional details on how SUMO handles parking capacity, demand, and the parking process. SUMO has been used for other parking-related studies (Codecá et al., 2018).

The research team developed a set of scenarios and evaluated their traffic performance.

4.1. Study Area Overview

The study area includes three analysis zones in San Francisco, representing residential, commercial, and mixed use (see Figure 7). The three zones are located in a busy district in San Francisco that includes office, retail, and general downtown areas. These areas are also Traffic Analysis Zones (TAZs) in the Metropolitan Transportation Council Activity Based Travel Demand Model (MTC-ABM).

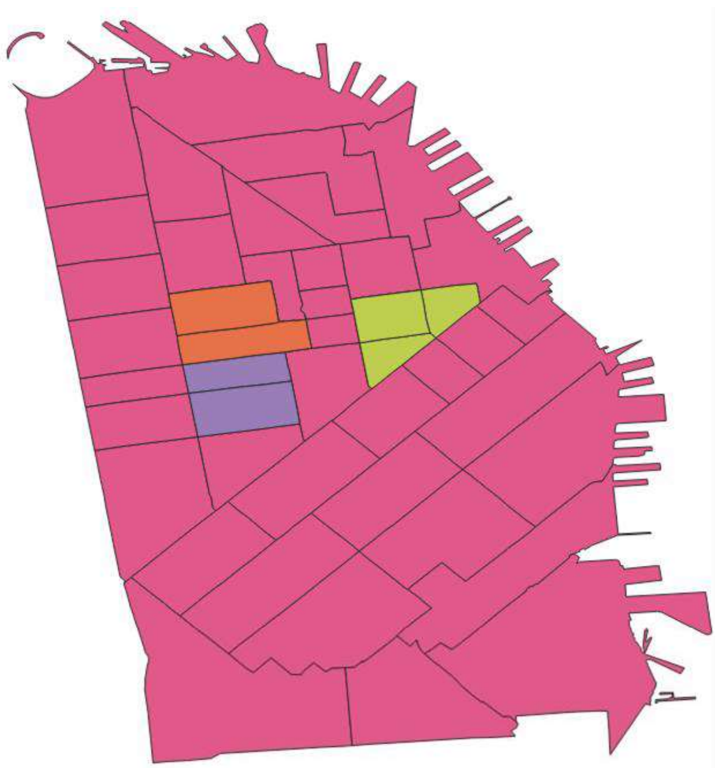


Figure 7. Study Areas in San Francisco (Mixed = Purple; Commercial = Green; and Residential = Orange)

Additionally, the team identified on-street and off-street parking locations from the SFpark website. With the infrastructure information, the team designed the transportation networks to use in SUMO. Figure 8 depicts the networks for the three study areas. It is important to mention that the areas were expanded on each side with an additional block to allow for vehicle activity on the periphery.

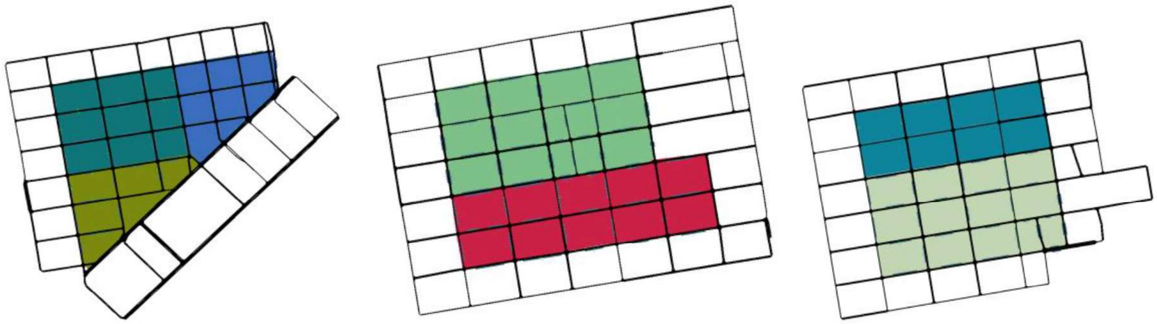


Figure 8. SUMO Networks (Left = Commercial; Center = Residential, and Right = Mixed-use)

Moreover, Figure 9 provides a more in-depth description of the land uses for each of the three sub-areas. The commercial area includes mostly Downtown general, retail and office; the residential area ranges from low to high density as it approaches the more commercial district; and the mixed-use area includes medium and high-density residential with Downtown retail, general and support land uses.

4.2. Trip Data

As mentioned, the travel demand data is modeled by integrating MATSim with the MTC-ABM (Rodier et al., 2019). Based on the geometric information given by the network in Figure 8, travel data in each TAZ was split out from information of time, type and travel direction for each area. The parking demand, on the other hand, is based on the travel data with the consideration of parking duration and route design for each vehicle. The truck data is based on the trip generation models (based on commercial establishments, employment and industry segment), and estimated share of daily residential deliveries (Jaller et al., 2013b; Jaller et al., 2015a; Jaller et al., 2015b; Holguín-Veras et al., 2017). Table 5 shows the estimated trucks trips.

Table 5. Truck Trip Demand per Time of Day

	AM (6-9)	MD (9-15)	PM (15-19)	Evening (19-21)	Night (21-6)	Total
Commercial	37	491	173	135	28	864
Residential	33	444	156	122	25	780
Mixed	42	561	197	154	32	986

Additionally, from the MTC-ABM and MATsim models, Figure 10 shows the car and taxi demand for the three areas across the various segments of the day. Specifically, the trip demand for car and taxis is split between ‘into’ and ‘out of’ the study area. Out represents trips that go out of the study area within the time segment, into represents incoming trips from outside areas to this zone, and net-into reflects the net trips between incoming and exiting the zone. The data also shows parked vehicles (less than 2 hours, and more than 2 hours), and other vehicles circling around the area.

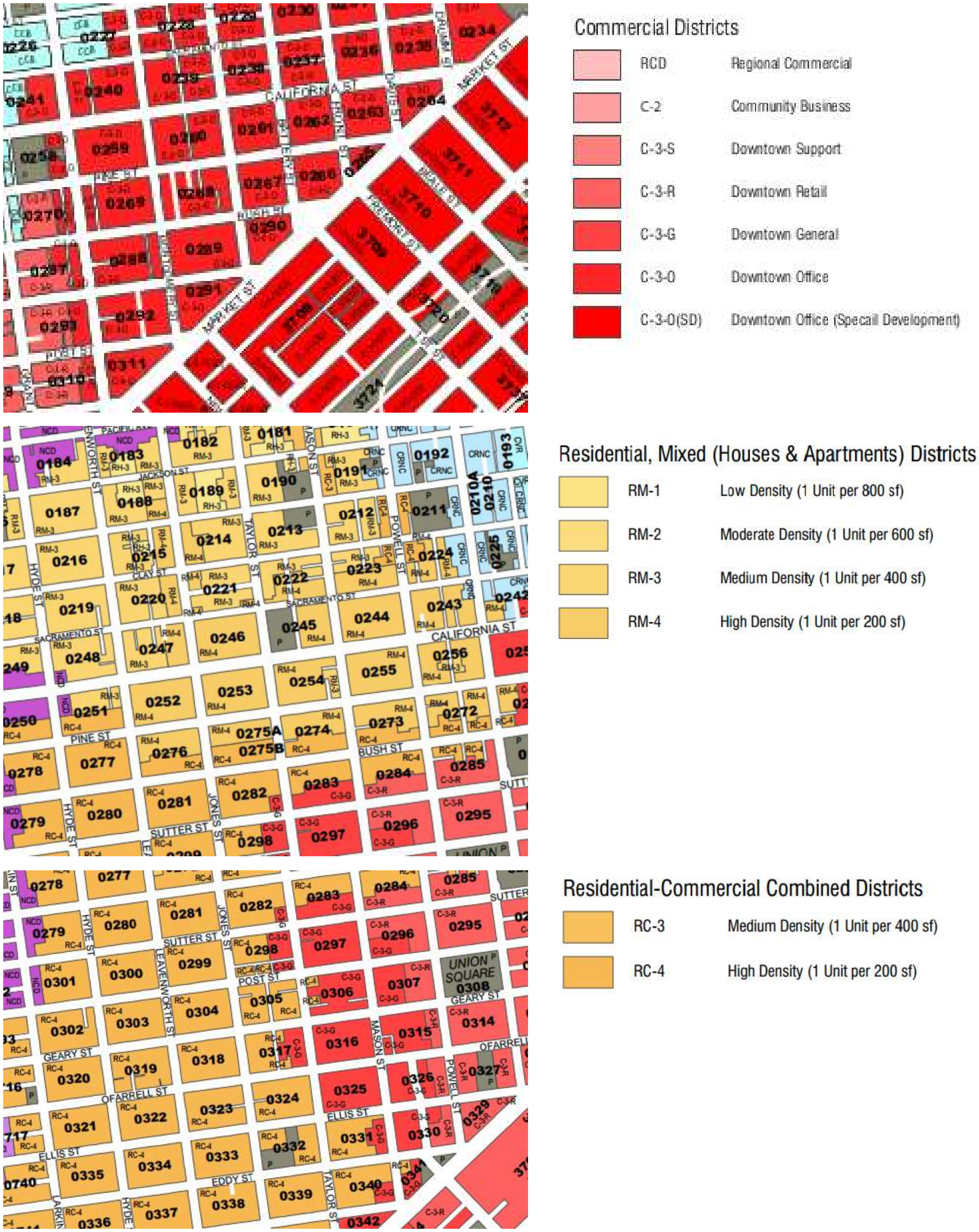


Figure 9. Study Areas in San Francisco (Land Uses) (San Francisco Planning Department, 2020)

For the commercial area, parking demand reaches its highest during the midday period. Many trips will park for more than 2 hours in this region. The net parking demand of the study area will reach up to around 15,000 vehicles with parking availability of about 7,595 at most, if taxis do not leave the area to relieve the parking deficit.

From the residential area, as expected, most of the vehicles leave during the morning. Throughout the day, parking demand does not reach the higher levels experienced in the commercial area, and taxis are only a small share of all trips/vehicles.

Finally, for the mixed-use area, as reflected by the share of residential and commercial, the number of vehicles exiting the area in the morning is smaller than for residential. Overall, there are twice as many trips out as in the residential area, but a much lower number than is seen inside the commercial area.

4.3. Curb Access and Parking

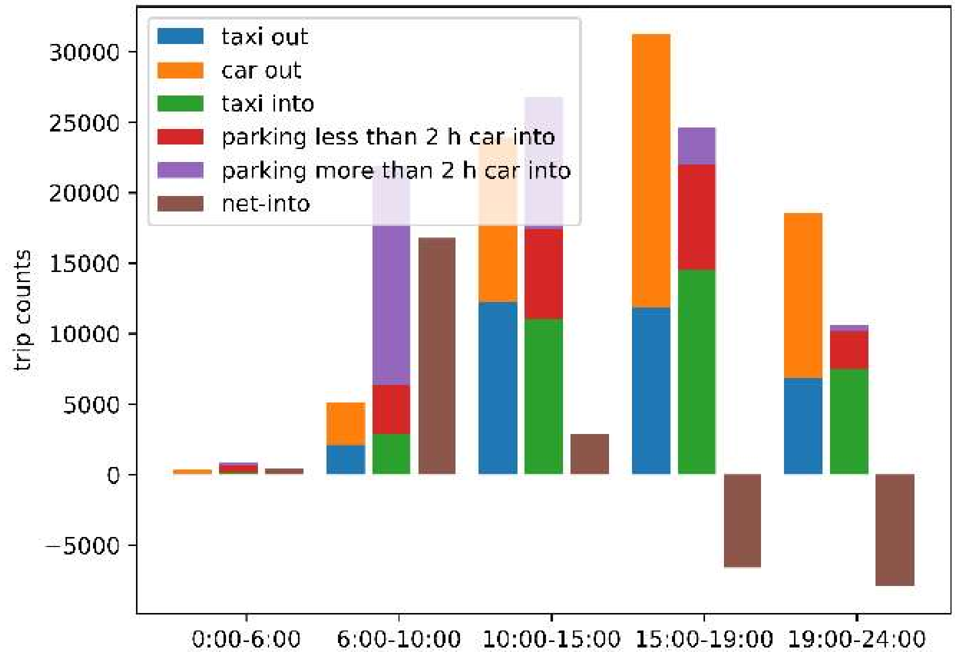
Overall, the analyses consider private vehicles, taxis or ride-hailing, and commercial delivery vehicles. As mentioned before, SUMO does not necessarily reflect the parking and curb access behaviors, thus the team developed a set of potential behaviors based on informed assumptions from the literature. These include assumptions about designated parking areas, parking time limits, real-time information, reduced occupancy targets (design demand/supply ratio to be less than 100%), and auto enforcement for illegal parking behaviors such as double parking.

Different vehicle types can be defined to exhibit different behaviors by utilizing the *rou* file. Each type of vehicle behaves differently when parking, loading, and unloading. This can be further implemented in the SUMO configuration file and the Python interface.

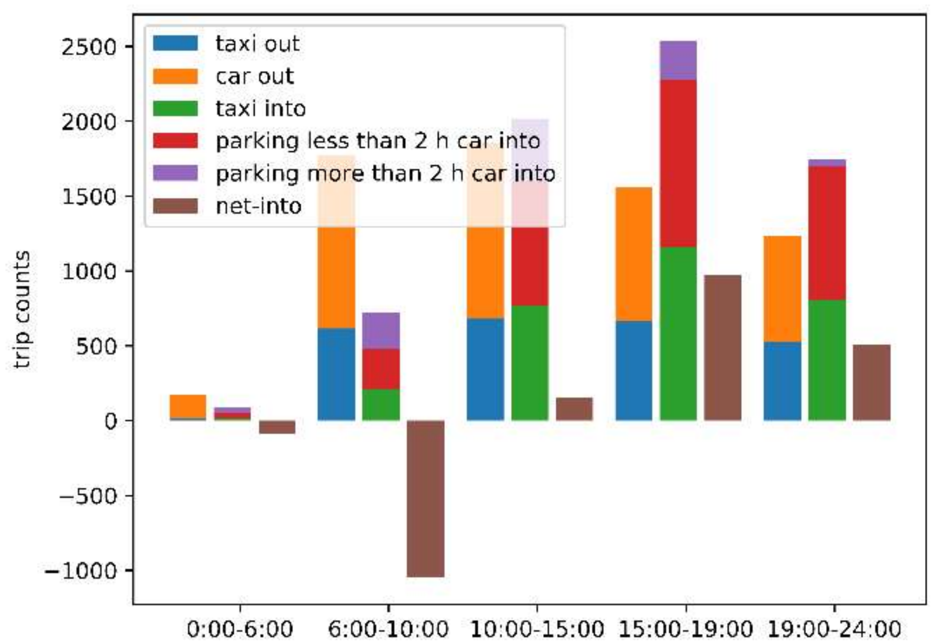
The trips in the three areas are shown below. There are about 168,704 daily trips considered in SUMO modeling for the commercial area, with 7,595 available off-street parking spaces and 645 on-street parking spots. Figure 10 also shows the trips in/out of the area for different time periods showing great variability during the day. For example, there is a 15,000 off-street car parking demand during the morning period (6-10 AM), while there are only 7,595 off- street parking spaces in the area. In the mixed-use and residential areas, however, there is not a parking space deficit.

Table 6. Trips Demand and Parking Supply (SF parking) in Study Areas

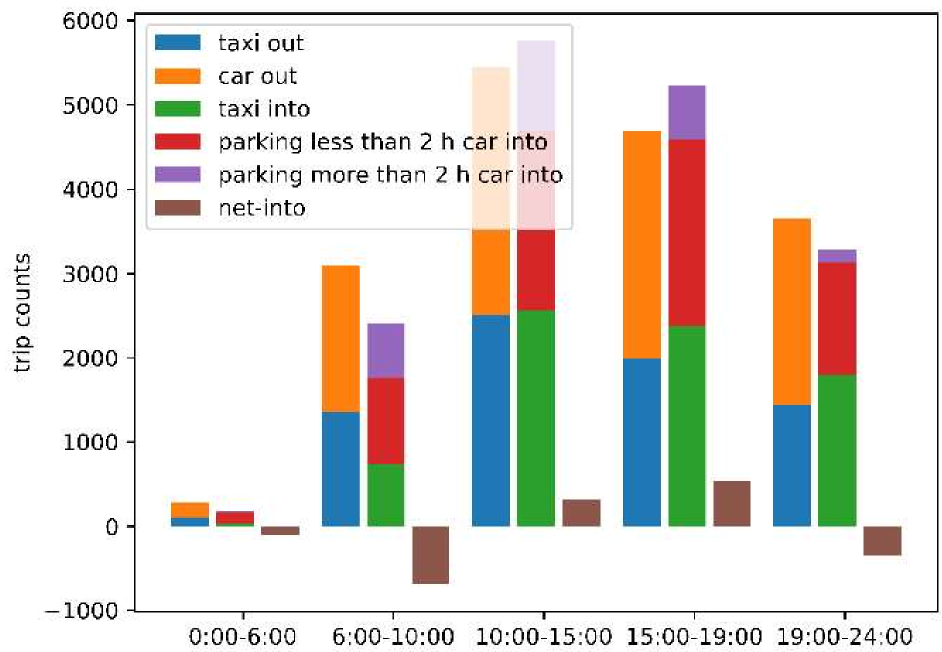
	Car/taxi/freight ratio	Total Trips	Off-street parking	On-street parking
Commercial	96,211/71,630/863	168,704	7,595	645
Residential	8,164/5,788/799	14,731	1,258	1,328
Mixed-use	18,919/14,995/987	34,901	2,749	942



Commercial



Residential use



Mixed use

Figure 10. Trip Demand in Study Areas

The route choice in SUMO is based on the shortest path algorithm. It is realistic in some cases, but not in serious congestion conditions. Vehicles might change their destination and/or re-route instead of following the shortest path rule and waiting at the intersection. Based on the TraCI interfering, vehicles near their destination (defined as less than three road links to their destination) will change their parking target to the next link they can access, and others will randomly re-route to their destination after turning to the next link they can access. When no parking is available at the destination, parameters such as distance, capacity, and time are weighted in the parking strategy of SUMO itself. In areas where there is no available parking, this configuration causes vehicles to stop and wait until spaces become available. This parking behavior is used as the control (baseline) scenario. The details of the other behaviors are discussed next.

4.3.1. Behavior 1: Searching for Parking (Circling Around)

TraCI package assists the interface between Python and SUMO. The package obtains information about a given vehicle, including waiting time, destination, route, and current position. TraCI can also determine the new stop, destination and route of each vehicle. With the help of this package, more realistic parking behavior (i.e., circling around) can be implemented. The package uses a probability distribution that randomly decides which direction the vehicle will turn while searching for a parking spot. In general, the probability of turning behavior is P, where the probability of continuing straight is greater than turning right, > left, and > U-turn. Figure 11 illustrates the simulation decision-making process for this scenario.

The key parameter is the turning probability. In Lan and Davis (1999), 0.3, 0.6, and 0.1 are used for left-turn, through, and right-turn movements. Tonguz et al. (2009) uses 0.25, 0.5 and 0.25 for left-turn, through, and right-turn movements of transit. This study used 0.2, 0.5 and 0.3 for left, through and right-turn movements of transit.

4.3.2. Behavior 2: Designated Area for Loading and Unloading or Drop-Off

The team gathered information for all on-street parking. Unless otherwise specified, they are available to all types of vehicles including ride-hailing, private cars and trucks. However, the lack of established designated loading/unloading areas makes it difficult for ride-hailing and trucks to find parking, leading to further congestion. This problem can be addressed by modifying the network such that certain areas are designated for these purposes. Available parking is specified as designated parking or parking available to all. For example, two spaces in one lane can be specified for loading/unloading, while the remaining space in the lane might be open to all. With the vehicle type defined in rou.xml file, different parking targets can be assigned to different vehicles.

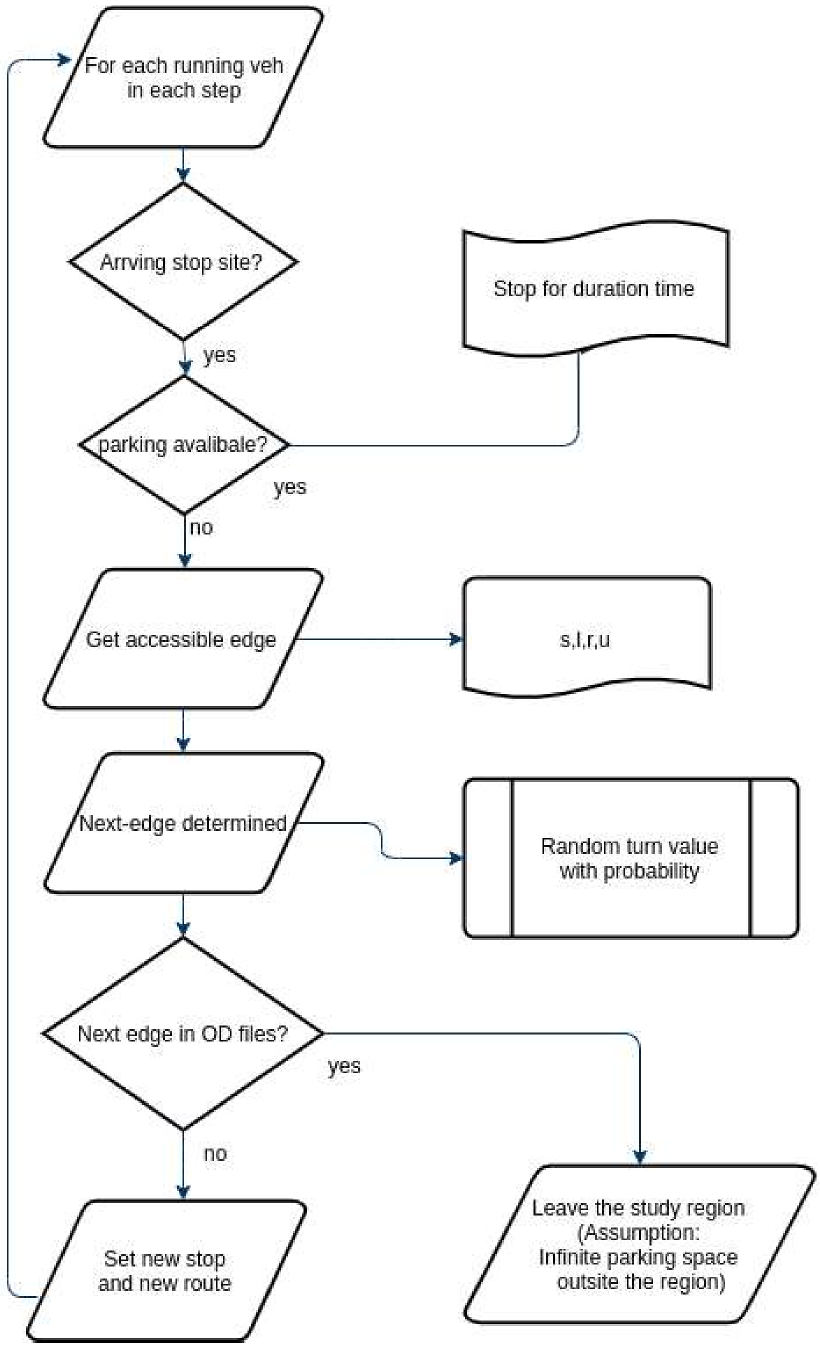


Figure 11. Behavior 1 – Circling Around for Parking

The simulations assume a baseline pick-up and drop-off time of 60 seconds. When evaluating these behaviors, the study assumes a number of scenarios reflecting different allocations of curb-space (proportion of parking spaces) for dedicated loading/unloading areas. The simulated proportions include 10%, 20%, 30%, 40%, and 50%. The pick-up and drop-off time is another parameter that influences the traffic. According to the TIA guidelines (San Francisco Planning Department, 2019), 60-65 seconds, 45 seconds, 27 minutes and 17 minutes are the average times dwelled for pick-up, drop-off, light-duty delivery truck on-street, heavy-duty truck on street, respectively. To simplify, 60 seconds are considered as the time needed for ride-hailing pick-up and drop-off, and 22 minutes as the time for truck loading/unloading. This commercial truck operations mainly reflects the time for commercial deliveries, whereas parcel deliveries could be as short as the times assumed for ride-hailing pick-up/drop-off.

4.3.3. Behavior 3: Real-Time Off-Street Parking Information

Considering the potential availability of on-street and off-street parking, parking decisions (on-street and off-street) can affect on-street parking demand. With real-time accessible off-street parking information (given in the rerouter.xml file), off-street parking vehicles can go to accessible off-street parking spaces without the need to search for parking availability. For the remaining vehicles searching for on-street parking, it could be assumed that their behavior is as defined in Behavior 1. The authors developed a set of scenarios that evaluated the impact of having real-time off-street parking information, assuming different levels of parking capacity (compared to the baseline of 100% capacity); the scenarios assumed 75% of the current situation (decreasing to 75%) and increasing to 125%, 125%, 150%, and 200%. These results can provide insights about the impact of real-time information in low capacity and high-capacity situations.

4.3.4. Behavior 4: Parking Time Limits

In busy downtown areas, setting a time limit will encourage some vehicles to park outside the busy area or to search for off-street parking. The base time-limit scenario is a 2-hour time limit for on-street parking. Other cases have time limits of 0.5, 1, and 1.5 hours. By defining trip parking times before running a SUMO scenario, vehicles that park less than the time alloted will be assigned an on-street parking area, while others will be assigned an off-street parking area. Using 1h as an example, vehicles under 1h will be assigned on-street parking and others will be assigned an off-street parking space. Both can circle around and have real-time off-street parking availability information. For vehicles assigned to on-street parking, their behavior follows Behavior 1, while the off-street parking vehicles will follow Behavior 3.

4.3.5. Behavior 5: Double Parking

This case models the effects of double parking, where double-parking vehicles are assigned with specific probabilities. With a specific double-parking rate applied, the number of double-parking vehicles varies. For example, when a rate of 0% is applied, double parking is not permitted, while with a high double-parking rate many vehicles could opt for double parking. There are various considerations regarding the legality of double parking; while it is not permitted in some jurisdictions, it is allowed in orders, especially when there are no available parking spaces within a distance threshold of the destination (e.g., for delivery trucks). “Double parking” vehicles will try to park at their target at first, and if there are no spaces available, they will double park. Other vehicles will continue to search for available parking if they cannot find a space at their original target, following Behavior 1. Figure 12 show the double-parking decision process. The key parameters for double-parking vehicles are parking time and parking proportion. According to (Gao and Ozbay, 2017), average double-parking time can be 0-1 minute, 1-5 minutes and 5-13 minutes, depending on the street type. The parking/standing time will be 1 minute for ride-hailing, 5 minutes for private vehicles, and 22 min for trucks in the base case. The proportion applied for ride-hailing will take the value of 10% for double parking, and 0.1% for private vehicles. The trucks will take a 100% portion, and the double-parking time will range in different scenarios to 5.5, 11, 16.5 and 22 minutes.

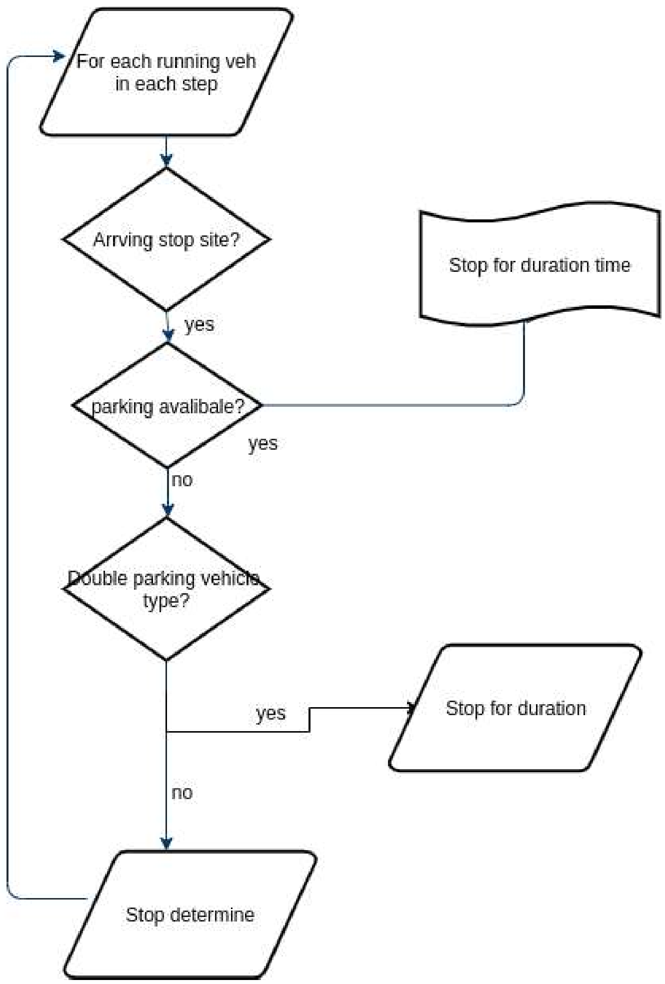


Figure 12. Double Parking Decision Making

4.4. Scenario Evaluation

SUMO provides trip information for each vehicle. For example, the travel time for each vehicle is its end time minus its departure time, while vehicle-miles travelled (VMT) for each vehicle is generated directly in the outputs. Other important factors to evaluate the performance of the various scenarios is related to the queue length and queue times as proxies for traffic conditions in the study area. Additionally, the authors estimated AVMT (average vehicle-miles traveled) and ATT (average travel time) to understand the performance at a disaggregate level. From these results, the team estimated the CO2 emissions in each scenario. Emissions are calculated based on the following equation[2] (Handbook emission factors for road transport version 3):

$$c_0 + c_1 va + c_2 va^2 + c_3 v + c_4 v^2 + c_5 v^3,$$

where v is the vehicle speed, and a is the acceleration/deceleration rate.

The simulations also assumed different levels of parking capacity and availability. The scenarios assume that parking capacity can be significantly increased through additional parking spaces, or other strategies such as angled parking. For instance, angled parking (e.g., 8' width with 16' length at 45 degrees) increases the overall supply compared to parallel parking, which can be applied to commercial districts where parking is scarce. The study assumes angle parking as a potential way to increase the number of parking spaces, though, angle parking can be achieved at the expense of road lanes or sidewalks and could have detrimental effects on traffic flow. However, the analyses are meant to provide an indication of the impacts of different parking behaviors and are not curbside design guidelines.

4.5. Limitations

SUMO is a microscopic simulation software, and the size of the study area, and vehicle volumes can affect its ability to simulate. For large instances, modelers typically scale down capacity and demand, and then expand the results to reflect total demand. Other limitations include strict lane choice modes, no modeling of overpassing, and predefined shortest routes. Travel route might also be overestimated by the route design of vehicles, especially when considering the travel behavior of taxis.

[2] https://sumo.dlr.de/docs/Models/Emissions/HBEFA3-based.html

5. Simulation Results

The team evaluated several scenarios to test the systems' performance for the various parking behaviors. Considering the stochastic nature of the simulations, and the computational resources and simulation times, the team conducted three replicates for each scenario. For each scenario, the team analyzed VMT (VKT), total travel times, queue lengths and queue times, as well as estimated emissions. APPENDICES B, C, and D include the Figures for each of the simulation runs and scenarios. The following sections discuss the results for the residential, mixed use, and commercial areas.

5.1. Residential Area Analysis

5.1.1. Parking search & informed off-street parking

The results assume the search for parking (Behavior 1) as the reference case. Circling around searching for parking increases VKT and leads to congestion, especially when parking capacity is limited (see Figures 14-17 for results). It is important to recall that the residential area has the lowest traffic and parking demand of the three study areas. When assessing changes in parking capacity (up to double), the simulations only show a slight decrease in total VKT (of about 1%) from the base case (parking search). Similarly, under different penetrations of off-street parking availability (knowledge) information, the results show almost twice the decrease in VKT, though still representing a max of between 2-3% VKT reduction. These distance reductions have a less than proportional decrease in total travel times, with total reductions lower than 1%. While the reductions are very small in terms of distance and travel times, there are some improvements in queuing times at intersections. For example, a 50% capacity increase could reduce queue times by 5%. Overall, the simulations show that changing conditions due to increased parking capacity can help decrease CO2, e.g., a 50% increase in parking capacity can result in 20% emission reductions.

5.1.2. Designated loading and unloading areas

The simulation results show that as more parking is reserved for truck and taxi/TNC pick-up and drop-off activities, overall VKT, travel times and emissions in the system tend to increase (see Figures 18-21). While the three simulations show high variability, the results show that the impacts are more significant as the percent of reserved spaces is over 30% (Figure B22). However, as with the other results in this mostly residential area, the impacts are minimal (less than 1%). The simulation showed more impacts in average queue lengths increasing more than 20% for the cases where parking in mostly reserved for these operations (Figure B22).

5.1.3. Parking time limits

When analyzing the parking time limits of .5–2 hours, the results showed varied behaviors. Figure B26 shows the changes in VKT due to the impacts in parking time limits. The results may be affected by searching for parking and other behaviors, as longer parking time limits will reduce parking availability, causing vehicles without parking to exit the area, thus increasing emissions (Figure B28). Travel times (Figure B27)show a consistent pattern with VKT, increasing with the time limits, and then reducing due to the searching behavior driving vehicles out of the system. Overall, with reduced parking availability due to longer parking time limits, the overall queuing times and lengths change by around 1%. There is also a minor change in travel distance, travel time and emissions between different time limits.

5.1.4. Double parking scenario

Usually, double parking can provide relief to commercial vehicles picking-up and dropping off passengers or cargo, when no parking is available, however, double-parked vehicles can create congestion and reduce safety. These scenarios are intended to show the impact of double-parked vehicles by considering different shares of double-parking activity. Double parking might influence traffic greatly. Forbidding double parking might lead to improved conditions, though it could affect the ability to perform commercial delivery operations.

In the considered residential area, the results (Figures 26-29) do not show significant differences in total VKT, except that double parking reduces the travel distance due to vehicles not circling for parking. However, this results in increased travel times and queues in the system (though still minimal increases, due to their low impact in residential areas). The results show that queues can increase in time and length by 5% with a higher penetration of double-parked vehicles (Figure B36). These results lead to large emissions impacts, with up to 20% increases in CO2 emissions due to many double-parked vehicles.

5.2. Mixed-use Area Analysis

5.2.1. Parking search & informed off-street parking

Consistent with the residential area case, the results show the impact of the first behaviors about parking search activities (i.e., circling) and the availability of off-street parking information. As expected, the results show that as parking availability increases, the distance traveled reduces. While the reduction in VKT in this scenario is still very small, interestingly, the magnitude of the reduction significantly changes with additional off-street parking availability (see Figure C37). Similarly, increases in parking capacity decrease queue times and lengths (up to 10% for a doubling in parking capacity) (see Figure C42). However, these reductions do not significantly affect travel times, with reductions in the order of 1% (Figure C38). The results in Figure C39 show some significant changes in CO2 emission reductions, which can benefit by almost 30% in the extreme capacity case (though not much improvement after 50% increased parking capacity).

5.2.2. Designated loading and unloading areas

The results show a increase in VKT and travel times in the area with increases in designated loading and unloading areas, when more parking space is substituted for temporary locations. However, while the increase in VKT is minimal (Figure C43), travel times could increase by more than 5% (Figure C44), resulting in more than 20% increases in CO2 emissions (Figure C45). Similar to the residential case, the impacts are more significant after a 30-40% allocation of existing parking spaces as designated loading/unloading areas. Queue lengths can increase above 20% as the percent of designated areas increase, whereas queue times increase only minimally (Figure C48).

5.2.3. Parking time limits

The results of the parking time scenarios show a decline in both VKT and travel time, as the parking times increase (Figure C49–A53). Unlike the residential area case, the parking demand distribution in this mixed-use area has a larger share of commercial vehicles, and a larger share of vehicles needing to park over 2 hours (Figure 10). With the time limits, these vehicles will not be able to park, thus they will exit the system. These behaviors have an impact on emissions, with a significant increase.

5.2.4. Double parking scenario

The results for double-parking in the mixed-use area show consistent trends similar to those observed in the residential area. However, the VKT and travel time effects, though minimal, show less sensitivity to double-parking penetration than seen in the residential area. Still, the extreme penetration of double-parking has a significant negative effect on emissions (Figure C57). Figure C60 shows the effect on queue times and length, and while the effect is very small, the trend correlates with changes in emissions.

5.3. Commercial Area Analysis

5.3.1. Parking search and informed off-street parking

Commercial land use has the highest volumes and parking demand of the three study areas. This has significant effects on system performance. For example, Figure D61 show the results of distance traveled, which is almost 10 times larger than in the other areas. The results also show that more information about off-street parking availability increases travel distances as vehicles reach those locations, however, the associated emissions decrease (Figure D63) with CO_2 reducing almost 40% for the extreme capacity scenario. On the other hand, as more parking capacity is available, the travel distance is reduced because of less circling around in the system, which is consistent with a reduction in travel time (Figure D62). Analyzing the effect on queue times and length, average queues significantly decrease as the parking capacity increases, with large reductions for the extreme cases, though the marginal improvements are minimal after a 50% increase in parking capacity.

5.3.2. Designated loading and unloading areas

Comparing the impact of providing designated areas for loading and unloading with the other cases, in commercial areas the 30-40% level still represents the point at which additional parking substitution begins to negatively impact the system (Figure D66–A71). However, the results show that increasing the number of dedicated areas up to that level continuously improves the system, and the effect is larger than in the residential and mixed-use cases. These behaviors are also reflected in the travel times and queues. Interestingly, the results show that the benefits in emissions (10%) reductions up to the 30% level are higher than the increases in CO_2 if additional designated areas are provided.

Considering that the results in the commercial area showed more sensitivity than the previous results, the team conducted disaggregate analyses related to the different vehicle trip components (passenger, taxi, and commercial vehicles), and changes throughout the day (morning and afternoon peak times). Figure D88-A96 summarizes these results. When observing the changes in distance traveled, interestingly, the additional allocation of designated parking spaces has a positive effect for commercial vehicles (decreasing distance), but distance increases for passenger vehicles and taxis, as previously explained. These effects are more acute during the morning peak periods than in the afternoon peak. However, at least for commercial vehicles, the distance traveled during the morning peak is significantly less than during the afternoon (because of lower volumes). Another important factor is that despite the decrease trends, the results still show a marginal effect after a 30% allocation of designated parking/loading and unloading spaces.

5.3.3. Parking time limits

For commercial areas, the simulation of parking time limits fluctuated significantly, more than is seen in the residential and mixed-use areas (see Figure D72–A77). Overall, the results show that having longer parking time limits has a detrimental effect on the system (longer distances and travel times), which consequently generates significantly more pollution. This could be explained primarily by the fact that the amount of parking supply is much lower compared to parking demand and reducing the parking space throughput in these locations by increasing parking time limits will negatively affect the system (up 30% increased emissions). On the other hand, lower time limits do not necessarily affect the system because of the parking time requirements for some vehicle types (e.g., trucks). The results show that, on average, the 1hr time limit is appropriate.

The team also conducted more detailed analyses to compare the changes during the day. The results show that in the morning peak, where the demand is not as large, the system behaves similarly to what is seen in the residential and mixed-use study areas. This is also explained by the fact that the 6 to 10AM time-period is when the system receives the largest influx of vehicles seeking to park more than 2 hours (as shown in the purple bar in Figure 10). In the afternoon, when the demand for 2-hr parking decreases, allowing vehicles to park in these slots does not generate benefits to the system.

5.3.4. Double parking scenario

Figure 58-61 show the double-parking scenario results for the commercial area. When evaluating double-parking, the results show a slight (up to 1%) increase in VKT and (up to 5%) travel times for the system, as the number of double-parked vehicles increases. Queue impacts are a bit higher, with increases up to 5%. Overall, these impacts have a negative effect on emissions, as they increase up to 9% with increases in the number of double-parked vehicles.

6. Summary and Conclusions

This study conducted a comprehensive literature review on several topics related to curb space management, discussing various users (e.g., pedestrians, bicycles, transit, taxis, and commercial freight vehicles), summarizing different experiences, and focusing the discussion on Complete Street strategies. Moreover, the authors reviewed the academic literature on curbside and parking data collection, and simulation and optimization techniques.

Considering a case study around the downtown area in San Francisco, the authors evaluated the performance of the system with respect to several parking behavior scenarios. In doing so, the authors developed a parking simulation in SUMO following a set of parking behaviors (e.g., parking search, parking with off-street parking information availability, double-parking). These scenarios were tested in three different (based on land use) sub-study areas representing residential, commercial, and mixed-use.

As expected, the results show that in busy areas (e.g., commercial), where parking demand may exceed parking supply, searching for parking might lead to traffic congestion and will cause extra emissions. Vehicles searching for available parking spaces not only slow down traffic, which will impair the efficiency of movement, but also cause a waste of time accessing the parking facility and producing additional emissions, particularly during peak hours when available parking spaces are scarce. Open real-time parking information is often used to help improve the traffic. With the simulations, the authors concentrated on average vehicle kilometers travel, total queue and average travel times, and CO_2 emissions.

In general, the average vehicle kilometers traveled has a decreasing trend as parking capacity increases (assumed feasible by geometric design of on-street spaces). It is easy to understand that as capacity increases, fewer vehicles need to search for parking, thus reducing VKT. Off-street parking availability information can help reduce by around 3% the average VKT in relatively low parking capacity. However, because the same occupancy weights (during simulated behaviors) are used for high parking capacity as in low capacity, vehicles in high-capacity scenarios also travel to more locations with more availability regardless of distance. In reality, people will choose to park closer to their destinations, which causes more distance traveled.

In different study areas, the policy implemented shows a different performance. Parking time limits in the residential area show little improvement as the time limit changes from 0.5 to 2 hour. In commercial areas, however, where demand may exceed capacity, it is very critical to manage the throughput of the parking spaces. On one hand, when demand for longer parking durations is lower, allocating spaces to have extra parking time limits negatively affects the system; on the other hand, when the need for more parking time increases (as was the case during the morning peak), allocating spaces to allow for more parking time decreases activity, travel time and emissions. These results support some of the Complete Street, and flex zone policies discussed in the initial sections of this document. In this way, an understanding of the disaggregate demands of the system by time of day, allows for the optimal allocation of space (e.g., short- versus longer-term parking, or designated loading and unloading areas).

As expected, designated zones for loading and unloading areas are much more essential in commercial areas compared to mixed-use and residential areas. While the system did not show significant improvements in the mixed-use and residential areas, providing additional spaces for loading and unloading improved the system more in commercial settings. However, it was a common finding that allocating more than 30% of the parking spaces as loading and unloading areas either did not improve the system further, or negatively impacted the system.

Overall, the work summarized existing literature on parking, and loading and unloading space management, and the simulation results show the performance of the system under a set of parking behaviors. While the model had limitations in assessing the dynamic patterns of space allocation, the intraday analyses (morning peak, afternoon peak, and full day) highlighted the system performance differences. Further work should focus on the dynamic allocation of curb-space, which can take advantage of the temporal changes in the relationships between supply and demand; different technologies to gather real-time information to inform the dynamic allocation models; and consider the potential unintended consequences of such dynamic systems for specific system users. While the simulation did not consider prioritization in the space and parking allocation and behaviors, managing the curb could also consider multiple objectives. Several of the reviewed street design and curb practices available in different cities have already identified user priorities. The curb could then become a significant lever to foster behavioral changes. At the same time, it is important to acknowledge that different users (passengers or freight) will have different requirements in accessing the curb.

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8. Data Management

Products of Research

The project used the following data:

- **Zip-code Business Patterns Dataset**. Distributed by the U.S. Census Bureau. ZIP Codes Business Patterns provides annual statistics for businesses with paid employees within the U.S. at the ZIP Code level. The public data will help estimate concentrations of establishments for different industries in the study areas. The Census Bureau updates the data yearly.
- **MTC-ABM Data and Outputs.** The MTC-ABM is made available on the MTC website for the general public, along with the input data, and examples of transportation scenarios. The team will use the model and generate the results and user daily activity for the individuals in the study area. The team have made this data available as part of this project.

Data assembled by the project:

- **Curb Demand**. The team implemented freight trip generation models for the study area, and created a dataset at the zip-code level.
- **UMO Files**. The team generated the set of input files required to run the set of scenarios in SUMO. These files are compressed.

Scenarios:

- The team created separate files with the input data used for the various simulation scenarios. The data includes the sources and other relevant information.

Data Format and Content

The project used the following public datasets:

- **Zip-code Business Patterns Dataset**. The files used are saved in Comma-delimited (csv) format.
- **MTC-ABM Data and Outputs.** The team used the model and generated the results and user daily activity for the individuals in the study area. The files have been compressed and offered as a single compressed ZIP file.

Data assembled by the Project:

- **Curb Demand**. The sets of curb demand data are provided in Comma-delimited (csv) format.
- **MATsim Files**. The files are compressed and offered as a single compressed ZIP file.
- **SUMO Files**. The files are compressed and offered as a single compressed ZIP file.

Data Access and Sharing

Interested individuals will be able to access the data available through Dryad and should contact the Principal Investigator, Dr. Miguel Jaller prior to accessing the data.

The data should not be hosted in other locations and should only use the Dryad repository.

There is no private or confidential information.

Reuse and Redistribution

Dr. Miguel Jaller and the other co-authors of the work (identified in the Final Report) hold the intellectual property rights to the data.

Data will not be able to be transferred to other data archives besides the ones approved by the PI and Co-PIs.

The data can be used by anyone with proper referencing to the authors.

9. APPENDIX A. Complete Street Strategies

Complete Streets strategies have received increased attention from practitioners. Complete Streets are designed and operated to enable safe access for all users, including pedestrians, bicyclists, motorists and transit riders of all ages and abilities. Different cities and states enact varying Complete Street strategies to create a safe and effective community for all users. The following sections examine these varying strategies, and the users they aim to prioritize.

9.1. Pedestrians

9.1.1. Sidewalk Widening, Bulbs, Art and Furniture

These features encourage people to walk by providing greater safety and attractiveness. ITE's curb management guideline (ICMG) addresses the needs of pedestrians by giving strategies of curb extension, wider sidewalks and parklets. Curb extensions extend the sidewalk into the parking lane at intersections, making pedestrians more visible, shortening crossing distances, and slowing vehicle turn movements. Sidewalks can also be extended in the middle of the street to reduce the distance across the street and calm vehicle speeds. Parklets are spaces along walking paths where seating, patios, or other amenities are provided without disrupting the flow of human traffic. Curbside furniture, lighting, and public art are suggested to facilitate walking behaviors and make streets more attractive. These strategies can be implemented even further by creating pedestrian-only streets, which allow pedestrians to walk uninterrupted by other modes of transportation. Pedestrian-only streets also provide the option of allowing delivery access during non-peak-hours to ensure that necessary delivery schedules are maintained.

9.2. Bicyclists

9.2.1. Protecting and Building Bike Lanes

The implementation of dedicated bike lanes is critical for safe biking. Designated lanes for bikes and/or separate bike lane parking can reduce exposure stress of cyclists and enhance safety. Coloring the pavement in bike lanes, signs, signals, and traffic lights also play a role in bicycling safety.

9.2.2. Biking Storage Management

When not in use, bicycles must be stored in convenient places for their riders. In an urban space, this would require docking stations for bikes with space for them to be locked to a stable surface. Other companies are exploring self-locking bicycles that do not require additional infrastructure.

9.2.3. Bike-Transit/Taxi Integration

When bicycle infrastructure coincides with transit infrastructure, bicycle use is encouraged. One example of this strategy is creating spaces to store bicycles in bus, train, or taxi stations. Allocating space for bike parking near transit can also incentivize transit use by making transportation to a station more convenient.

9.3. Transit

9.3.1. Median Bus Lane / Busway, Bus Priority and Bus Queue Dump Lane

Using dedicated bus infrastructure makes bus services more efficient and reliable, encouraging people to take the bus. Bus lanes can also be designed in the median of a road. This minimizes conflicts with traffic turning and on-street parking and improves the speed and efficiency of transit services. Bus lanes are often separated from other traffic by special pavement markings, such as continuous red paint. A “bus queue jump” refers to a short transit lane near an intersection that allows buses to bypass vehicle congestion. Peak-period bus exclusive lanes and bus queue jumps are also suggested because longer peak-period bus exclusive lanes can become loading or parking at off-peak times. Such priority for transit, as well as transit signal priority, is suggested by some CSGs.

9.3.2. Median Bus Boarding Island

Boarding islands for transit loading/unloading can enhance safety for riders and make transit services more efficient. Bus shelters and other transit-related amenities could be provided in the road median, releasing constrained curbside. One CSG suggests bus bulbs longer than 25 feet, as well as passenger loading bays. These indentations in the curb allow a bus to stop completely outside of the traveled way. CSGs also consider transit riders, and suggest upgrading transit stop amenities, such as shelters and transit schedules in shelters, which provide more comfortable conditions for transit services.

9.4. Ride-Hailing

9.4.1. Geofencing

Geofencing creates a virtual geographic boundary for pick up and drop off areas. This allows both drivers and riders to locate one another with greater ease. Designating on-street spaces per block for the exclusive use of carshare provides greater access to shared vehicles. Many large buildings such as airports will create designated areas for ride-hailing services, further facilitating this process. The On-Street Shared Vehicle Parking Permit Program is an example of the Geofencing strategy for for-hire vehicles. LA’s Complete Strategy mentions on-street carshare parking exclusively for carsharing, reducing parking demand, vehicle miles traveled, and auto emissions.

9.5. Freight

9.5.1. Paid Access to Freight Zones

With this tool in effect, vehicles are required to pay to use freight loading and unloading zones. This requires users to purchase and display a permit on their vehicle or pay-by-cell immediately after parking. Freight demand is managed by using paid permits to control loading zone availability at designated times and reduce the duration of occupancy.

9.5.2. Charging Delivery Vehicles in Peak Time

This Complete Streets strategy charges delivery vehicles during peak-time and encourages the use of smaller vehicles for last-mile deliveries. For instance, the Off-Hour Deliveries (OHD) Program in New York is intended to increase the number of goods deliveries between 7 pm and 6 am; this time reflects greater availability of curb space and lower pedestrian volumes. In Manhattan, delivery vehicles must pay a $20 charge to access critical points of entry. Charging delivery vehicles during peak times encourages off-peak activity.

9.5.3. Staging Zone

Staging zones are dedicated spaces on the street that are time limited to next-in-queue transportation trucks. Allocating a space for trucks waiting to access single access off-street loading/unloading points in high demand building locations can reduce incidents of large vehicles illegally stopping and blocking lanes or, alternatively, circling around the block unnecessarily waiting the next-in-queue opportunity.

9.5.4. Wider Parking Zones and Turning Radii

Larger freight trucks take up more space on streets and have more difficulty parking and turning when streets are narrow. By widening parking zones and street turning radii, large freight vehicles can more efficiently make deliveries. These are best implemented on streets with high traffic volumes.

9.5.5. Last-Mile Deliveries

By using smaller vehicles for last-mile deliveries, large trucks can be more efficient in delivering large volumes to key delivery zones, at which point smaller vehicles can take deliveries to their final destinations. This allows the large carrying capacity of trucks, as well as the efficiency of smaller vehicles, to be most effectively utilized.

9.6. Parking Availability

9.6.1. Demand-based Parking Pricing

Demand is determined by observing an area's driver and passenger behavior, as well as understanding the total demand at different times and locations. Demand-based parking prices change dynamically with demand, increasing the number of available metered parking spaces in peak. For example, the SFpark pilot collected and distributed real-time information about available parking, helping drivers find open spaces quickly, which reduced traffic stress and street congestion. SFpark periodically adjusts meter and garage pricing to match demand. Demand-responsive pricing encourages drivers to park in underused areas and garages, reducing demand in overused areas. Similarly, Penn Quarter/Chinatown Parking Pricing Pilot changes parking prices with time (off-peak or peak) to manage demand in peak and off-peak hours.

9.6.2. Time Limit and Time-of-Day Restriction

Time limits can be implemented to increase availability of parking at places with high demand for short duration parking. Time-of-day restrictions can be used in areas with significant peaking demand, balancing the needs of all users and using curb space more efficiently and flexibly.

9.6.3. Inclusion of Off-Parking

Priority Parking Programs or paid parking permits can be implemented for a given neighborhood or zone to reduce the incidence and/or duration of non-resident parking. The SFpark program mentioned above also considered off-parking to make more parking spaces available.

9.6.4. Reduced Occupancy Target

Lowering the occupancy target below 100% means that at any given moment, not all parking spaces will be full. This reduces additional time spent by cars searching for parking spaces. NCSMG gives more specific information about how to choose occupancy rates.

9.6.5. Angle Parking

Parking areas could be designed as angle parking rather than parallel parking to get more parking spaces. This requires more land use, but facilitates parking.

9.7. All Users

9.7.1. Flex Zones

Changing curbside to flex zones allows parking to change for several cases, with the same area of curb space used for multiple functions simultaneously. Designating curb spaces as Shared Use Mobility (SUM) Zones for ride-hailing passenger pick-ups and drop-offs is ideal during peak hours, so the same space can serve more people than a single parking space would. These spaces could be converted back to regular parking spaces or be designated as commercial delivery zones in off-peak, or when combined with off-peak deliveries. Uber and Lyft are working with cities like Washington D.C. and San Francisco to establish such designated zones; one example is the On-Street Shared Vehicle Parking Permit Program in San Francisco. Designated pick-up and drop-off spots for ride-hailing are painted or signed on the curb. The pilot of the program tested the permitted use of about 210 on-street parking spaces at 140 locations across the city.

9.7.2. Road Diets

Road diets reduce the amount of space available for automobile infrastructure. Road space can then be reallocated for multiple functions, such as bike lanes and widened sidewalks. By changing the space for on-street parking, widening freight delivery zones, and narrowing space for drivers, cars will drive more slowly, which increases safety.

9.7.3. Automated Enforcement

Automated enforcement of curbside and transit lanes, such as camera capturing, can improve the efficiency of the entire street. Automated parking enforcement is effective against parking in transit lanes and double-parking. The lowest effective fine should be used for illegal parking, and higher fines should be used when needed.

9.7.4. Moving Loading and Access Around the Corner

This design looks at access locations for freight deliveries, making points of access further from the destination building. The access location could be moved to a neighboring street for freight loading/unloading, and could similarly used for alternate locations for passenger's pick-up/drop-off.. This reduces congestion near popular destinations and allows other users to access buildings more readily.

9.7.5. Living Previews

Living previews are also called pop-ups. They yield great participation of residents who observe and comment on proposed projects. One example is the Vision Zero actions in San Francisco. With the goal of eliminating all traffic deaths in San Francisco, Vision Zero relies on a citywide effort. The project includes protecting bike lanes, building new traffic signals and pedestrian countdown signals, and making crosswalks more visible.

9.7.6. Commuter Shuttle

Curb space for commuter shuttles encourages commuter shuttle use while decreasing single occupancy vehicle trips. Commuter Shuttle Programs and Private Transit Vehicle (PTV) permit programs strive to regulate shuttles and private transit vehicles. Commuter Shuttle Programs create a network of up to 125 shuttle stop locations for shuttle loading and unloading, and enforce shuttle regulations to increase safety. PTV formalized private transit to reduce unsafe passenger loading, minimize travel on restricted streets, and collect data for a travel demand analysis. The Car-Free Living Program gives residents who participate bonuses to encourage them to take for-hire vehicles instead of driving private cars.

9.8. Regional Plans

The Complete Streets strategies examined in the previous sections have been implemented in several cities' regional plans. Each of these intends to create "Complete Streets," prioritizing safety and accessibility for all curb-space users. The following descriptions will examine and summarize key findings from several different regional plans.

9.8.1. San Francisco Better Street Plan

The San Francisco Better Street plan concerns creating better streets for driving, riding, biking, and walking. Vehicle sharing is key to reductions in private car transport and the need for parking spaces. However, there are pieces of private car infrastructure that still merit improvements, such as providing real-time information about parking. With real-time parking information, cities can implement demand-priced parking, which adjusts parking rates based on demand. Smart app (SFpark) can help to give this real-time information to drivers with costs and times, allowing drivers to make travel choices ahead of time. This plan also prioritizes transit, walking and bicycling. Curb ramps and sidewalk widening are designed to enhance safety for pedestrians, increased lighting can provide visibility for pedestrians when crossing streets, and slowing down traffic is important to enhance safety. Upgrading transit rider amenities and dedicating lanes for transit to improve travel times were two means for upgrading transit and increasing ridership. Adding bike lanes and reducing stress exposure are mentioned as strategies to enhance safety for cyclists. Additionally, bicycle infrastructure can be further improved by integrating it with transit and taxi infrastructure. Freight routes are designated as “Routes with Significant Truck Traffic” when needed. Industrial streets are used for loading, shipping and deliveries. They are typically located in industrial areas with lower levels of pedestrian and car traffic. They must be designed to serve major freight and loading activities, and to meet the access needs for deliveries (Better Streets San Francisco, 2011).

9.8.2. Main Street, California: A Guide for Improving Community and Transportation Vitality

Integrating bike and pedestrian infrastructure into main streets is critical to producing attractive conditions for biking and walking. This includes the implementation of curb ramps, crosswalk markings, and widened sidewalks to enhance safety for pedestrians. Bulbouts can provide visibility for pedestrians and shorten the walking distance when crossing streets. Raised median islands can provide a crossing refuge for walking and reduce traffic conflicts. Because they enhance safety for pedestrians, they are also referred to as “pedestrian refuge islands” or “pedestrian crossing islands.” Lighting, furniture and other amenities for sidewalks are additional suggestions to facilitate walking activities. Developing a bicycle-transit integration program can also facilitate bicycle activities. Shared traffic lanes and bicycle lanes can be implemented for needed areas to facilitate biking.

This plan also mentions that slowing down traffic is important for enhancing safety. This could be achieved via road diets, narrowing traffic lanes, and setting lower speed limits. When applying a road diets strategy, lane reallocation decisions should be based on analyses of potential impacts to pedestrian, bicyclist, driver and transit rider mobility. Additional concerns include impacts on vehicle congestion, traffic conflicts involving all travel modes, the movement of freight, and associated maintenance concerns. Motor vehicle parking on-street, if feasible, can also enhance safety by providing a buffer between pedestrians and traffic. Angled parking, including forward (nose-in) and reverse (back-in), can provide more parking spots than parallel parking, but more curb spaces are required for angled parking than parallel parking. Cities can also provide space for roadside features like medians, bike lanes, sidewalks, on-street parking, transit stops and landscaping.

Transit-only lanes/ Bus-only turn lanes for right and left turns are designed to increase efficiency and consistency of transit service by segregating transit vehicles from other traffic. Queue bypass lanes are short transit lanes in intersections that enable buses to travel efficiently. Similarly, transit signal priority can facilitate efficient transit service. There are several designs for bus stops including in lane stops, bus bulbs and bus bays. Bus bulbs are longer than 25 feet and facilitate passenger loading. Bus bays, which are indentations in the curb, allow a bus to stop completely outside of the traveled way. Transit stop amenities such as shelters can provide more comfortable conditions for transit service (Caltrans, 2013).

9.8.3. North Carolina DOT Complete Street Planning and Design Guidelines

These design guidelines examine several aspects of Complete Streets planning considering the various users. One point made by the North Carolina DOT is the possibility of restricting parking and/or truck delivery zones if needed for a transit stop. Transit lanes and queue bypass lanes can facilitate efficient transit service. Bus bulbs for stops and amenities in stops can provide more comfortable conditions and increase ridership. Bicycle storage should be near transit stops to facilitate these activities. Bike lanes are critical for a safe bicycling activity. Curb ramps, crosswalk markings, and sidewalk widening are designed to enhance safety for pedestrians. Bulbouts can provide visibility to pedestrian and shorter the distance when crossing the street. Moreover, light, furniture and other amenities for sidewalk may facilitate walking activities (North Carolina Department of Transportation, 2019).

9.8.4. New Haven Complete Street Design Manual

The New Haven Complete Street Design Manual defines “pedestrian-only streets” as streets that can be designated “pedestrian-only” during peak periods, with delivery access during off-peak hours. Pedestrian pavements, crosswalk markings, tree belts and sidewalk widening are strategies designed to enhance safety for pedestrians. Bulbouts can provide visibility to pedestrians and shorten distances when crossing streets. Lighting, furniture and other amenities for sidewalks also facilitate walking activities. Bicycle storage should be addressed to encourage bicycle usage. Additionally, bus lanes and signs are critical for safe bicycling activity. Speed limits should be set under the speed the community desires, with speed humps being one useful design element to reduce vehicle speeds. On-street parking should be priced through meters and kiosks, placing an emphasis on automation. Residential parking permits should be used appropriately to manage driving demand in a specific area. Delivery access may be allowed in off-hours in pedestrian-only streets. In industrial areas with large volumes of truck traffic, wider travel lanes and larger curb radii are of greater priority (City of New Haven, 2010).

9.8.5. Complete Streets Design Guide - Los Angeles

Curb ramps and sidewalk widening are designed to enhance safety for pedestrians. Bulbouts are suggested to provide visibility for pedestrians, and shorten distances when crossing streets. Lighting, furniture and other amenities for sidewalk may facilitate walking activities. Because slowing down traffic is important to enhance safety, several suggestions are offered , bulbouts are raised curb extensions that narrow the travel lane at intersections or midblock locations can calm speed and decrease distance across street. Traffic speed can also be slowed by dividers/roundabouts. Bike lanes can be implemented in certain areas to facilitate biking. Median bus lanes can minimize conflicts with on-street curbside parking and vehicle turning movements, improving the speed and efficiency of transit services. Transit stop amenities such as shelters can provide more comfortable conditions for transit service. Median bus boarding islands refer to spaces built to accommodate bus shelters and other transit-related amenities on a median island, releasing curb space on otherwise constrained sidewalks. On-Street Carshare Parking is a problem that needs to be addressed. Carsharing reduces parking demand, vehicle miles traveled, and automobile emissions, and designating on-street spaces on each block for the exclusive use of carshare would provide greater access to shared vehicles. Back-in angled parking can provide more parking spaces than parallel parking. Commercial loading zones can provide access for loading/unloading and reduce double parking by delivery vehicles. Commercial loading zones should be applied in select locations along commercial corridors where on-street parking is scarce, or where high volumes of deliveries currently occur. Loading zones should be consolidated at midblock locations if feasible, as this minimizes conflict with vehicles near intersections. An effective turning radius is safe for walking, and provides enough space for large vehicle turning (Los Angeles City Planning, 2016).

9.8.6. Pasadena-Design-Guidelines - Complete Street

Curb extensions, or bulbouts, can provide visibility for pedestrians and shorten crossing distances. Parklets provide extra space with amenities for sidewalk areas, encouraging walking activities, especially in downtown areas. This guide also mentions that slowing down traffic is important to enhance safety. The target width for on-street parking should be 7.5 feet. However, the width of parking lanes can be adjusted to as narrow as 7 feet and as wide as 9 Feet. A parking lane of 7 feet could cause a visible stress for other lanes, leading to slower speeds. A wider parking lane of up to 9 feet may be necessary when there is a commercial loading zone, bus layover facilities, or freight parking. Bike corral/ bike share stations address issues related to bike parking and encourage bicycle travel. Bus loading and passenger waiting areas can provide more confortable transit service experiences. Building intersections with large curb radii make turning easier, but should be limited to locations where they are absolutely necessary. Wider parking for commercial loading zones can facilitate loading/unloading activity. Shared access for bike, pedestrian, delivery, and local vehicular traffic in the same right-of-way utilizes curb space efficiently (Transportation, 2017).

9.8.7. Central County Complete Streets Design Guidelines - Alameda, CA

To prioritize automobiles, cities can reduce curb zones, widen travel lanes, and construct additional parallel or angled parking. To prioritize bicycles, cities can narrow pedestrian zones, allocate a greater share of curb zones for bicycle parking, and narrow travel lanes. To prioritize pedestrians, cities can widen pedestrian zones and narrow vehicle travel lanes. To prioritize transit, cities can widen pedestrian zones, widen travel lanes for buses, and create curb zones for bus stops. To prioritize freight, cities can narrow pedestrian zones, provide parking for truck unloading, and widen vehicle zones for large vehicles. Which strategy a city chooses to implement depends on its particular urban, suburban, industrial, or rural land use context. While urban contexts would prioritize transit and pedestrians, suburban would prioritize parking, and industrial would prioritize freight (Alameda County Transportation Commission, 2020).

9.8.8. *Monterey Bay Area Complete Streets Guidebook*

This guide provides critical information regarding the development of Complete Streets as a function of street type, user prioritization, and land use (Santa Cruz County Regional Transportation Commission, 2013).

Table A7. Monterey Bay Area Complete Streets Guidelines

Type	Description	User prioritization	Land use place types
Main Streets	Pedestrian-oriented "destination" streets; land uses: mixed-use, commercial, entertainment, office, civic; short blocks, grid street pattern; can be used as a flexible space for community events (ex: farmers markets)	1. Pedestrians 2. Bicyclists 3. Transit 4. Autos/Trucks	Urban Mixed-Use; Town Commercial; Town Mixed-Use; Rural-Town Commercial; Institutional
Avenues (collector)	Bicycle and transit-oriented streets connect neighborhoods to job centers and commercial areas. Higher speeds than main streets; land uses: diverse mix of land uses including but not limited to residential, schools, parks, neighborhood commercial and commercial	1. Bicyclists 2. Pedestrians 3. Transit 4. Autos/Trucks	Urban Multi-Family Residential; Multi-Family Residential; Neighborhood Commercial; Town Multi-Family Residential; Town Mixed-Use; Institutional; Open Space/Recreation
Boulevards (minor arterials)	Higher speeds and volumes of automobile traffic than avenues, but more pedestrian and bicycle-friendly than parkways	1. Transit 2. Autos/Trucks 3. Bicyclists 4. Pedestrians	Multi-Family Residential; Neighborhood Commercial; Regional Commercial; Employment Center; Neighborhood Mixed-Use; Institutional; Open Space/Recreation
Parkways (major arterials)	Auto-oriented designed to move high volumes of vehicular traffic quickly; land uses: major destinations such as regional commercial, academic institutions and visitor-serving uses	1. Autos/Trucks 2. Transit (BRT/Rail) 3. Bicyclists 4. Pedestrians	Employment Center; Airport; Institutional; Open Space/Recreation
Local Streets	Low-speed and low-traffic volume shared streets (bicycle, pedestrian & auto) with on-street parking; land uses primarily residential, neighborhood commercial, office, mixed-use, schools and parks	1. Pedestrians 2. Bicyclists 3. Autos/Trucks 4. Transit	Urban Single-Family Residential; Urban Multi-Family Residential; Urban Mixed-Use; Single-Family Residential; Multi-Family Residential; Town Single-Family Residential; Town Multi-Family Residential; Rural Town Residential; Institutional; Open Space/Recreation
Rural Roads	Mostly auto-oriented with few bicycle facilities for agricultural workers and long-distance cyclists	1. Autos/Trucks 2. Transit 3. School buses 4. Bicyclists 5. Pedestrians	Agriculture and Rural Residential; Exurban Residential; Industrial and Manufacturing; Open Space/Recreation

Type	Description	User prioritization	Land use place types
Scenic Roads	Mostly auto-oriented with bicycle facilities, some pedestrian facilities and access to natural resources	1. Autos 2. Bicyclists 3. Pedestrians 4. Transit 5. Recreational cyclists and hikers	Exurban Residential; Agriculture and Rural Residential; Open Space/Recreation

9.8.9. Complete Streets: A Guide to Best Management + Design Practice

This best practice guide provides design concepts, dimensions, and application details of Complete Streets. It also explores the transportation network in Auburn, California, including 16 different thoroughfare types. A toolbox (shown in Figure A13) includes 38 best practices of design techniques for integrating walking, cycling, public space, transit, and driving. Details about design, application and maintenance are also discussed in the guide (StreetPlans et al., 2017).

9.8.10. Unified Design Manual, City of Merced

Pedestrian network systems connect all parts of the community and enhance connectivity. Widened sidewalks, seating, refuge islands, and curb extensions are used to increase safety. Bike lanes and increased bike parking can be used to encourage biking. Designated passenger drop off areas with special paving or markings benefit ride-hailing services. Improving transit facilities enhances transit ridership. Merced California considers off-street parking and increasing the number of parking spots, suggesting that shared parking can be used when operations for the land uses are not normally conducted during the same hours, or when hours of peak use differ (Parkmerced, 2020).

9.8.11. Complete Street Design Handbook

Curb extensions and bicycle lanes can be used to enhance the safety of non-motorists. Transit stops and transit lanes can enhance the efficiency of transit. Truck lanes can be implemented in areas where truck activities are frequent. Mountable curbs can be used on corners for areas where large trucks or vehicles require access to constrained spaces. The use of smaller trucks in busy areas can be promoted, as well as reserving parking areas for commercial vehicles. Lane widths can be adjusted to balance the need of all users (Orange County Council of Governments, 2016).

9.8.12. Sacramento County Countywide Design Guidelines and Case Studies

Curb extensions and bicycle lanes can be used to enhance safety for non-motorists. The design of on-site circulation and parking lots should reflect the need for mixing and integration of modes (i.e., trucks, autos, transit, pedestrians, and bicycles). Industrial buildings should place auto parking adjacent to lobbies and public areas, and truck loading and parking adjacent to service and manufacturing areas (Sacramento County, 2018).

STREET TYPES

FACILITY TYPES	RH	RR	RSS	NG	RAS	CAS	RYS	RSU	RAU	CAU	BLVD	CS	DS	SUP	CA	PP
WALKING																
High-Visibility Crosswalk			•	•	•	•	•	•	•	•	•	•	•	•		•
Curb Extension				•	•	•	•	•	•	•	•	•	•			
Raised Crosswalk			•	•	•	•					•	•	•	•		•
Pedestrian Refuge Island						•				•	•	•				
In-Pavement Crossing Beacon					•					•	•					•
HAWK Signal				•	•	•			•	•	•					•
Rectangular Rapid Flashing Beacon				•	•											•
Leading Pedestrian Interval				•	•	•			•	•	•	•	•	•		•
CYCLING																
Shared Use Bike Path	•	•			•	•			•	•	•			•		
Protected Bike Lanes					•	•			•	•	•	•	•			
Buffered Bike Lanes					•	•			•	•	•	•	•			
Conventional Bicycle Lanes			•		•	•		•	•	•	•	•	•			
Bicycle Priority "Super Sharrows"				•		•	•	•	•	•		•	•			
Shared Use Lane Markings				•		•	•	•	•	•		•	•			
Bicycle Box				•	•	•	•	•	•	•	•	•	•			
Two-Stage Turn Queue Box					•	•		•	•	•	•	•	•			
Bicycle Refuge Island			•	•	•	•	•	•	•	•	•					
Combined Bike / Turn Lane			•		•	•		•	•	•	•					
Cross-Bike Markings			•	•	•	•	•	•	•	•	•	•	•	•		
Colored Pavement				•	•	•	•	•	•	•	•	•	•	•		
Bicycle Signal				•	•		•	•	•	•	•	•	•	•		

KEY

- SPECIAL DISTRICT
- URBAN CORE
- URBAN CENTER
- GENERAL URBAN
- SUBURBAN
- RURAL

RH: Rural Highway
RR: Rural Road
RSS: Residential Street - Suburban
RAS: Residential Avenue - Suburban
CAS: Commercial Avenue - Suburban
NG: Neighborhood Greenway
RYS: Residential Yield Street - Urban
RSU: Residential Street - Urban
RAU: Residential Avenue - Urban
CAU: Commercial Avenue - Urban
BLVD: Boulevard
CS: Community Street
DS: Destination Street
SUP: Shared Use Path
CA: Commercial Alley
PP: Pedestrian Passage

FACILITY TYPES	RH	RR	RSS	RAS	NG	CAS	RYS	RSU	RAU	CAU	BLVC	CS	DS	SUP	CA	PP
PUBLIC SPACE																
Interim Design Pedestrian Plazas								•	•	•	•	•	•			
Parklets										•	•	•	•			
Pocket Parks			•	•	•	•	•	•	•	•	•	•	•	•		
Bioswales			•	•	•	•	•	•	•	•	•	•	•	•	•	•
TRANSIT																
Bus Shelter				•		•		•	•	•	•	•	•			
Bus Lanes						•				•	•					
Bus Bulb						•				•	•					
MOTOR VEHICLES																
Speed Table / Raised Intersection					•		•	•	•			•	•			
On-Street Parking			•	•	•	•	•	•	•	•	•	•	•			
Safe-Sized Travel Lanes	•	•	•	•	•	•	•	•	•	•	•	•	•			
Turn Radii				•	•	•			•	•	•		•			
Road Diet			•	•		•		•	•	•	•	•	•			
Roundabouts (modern, mini etc.)			•	•	•	•	•	•	•	•	•	•	•			
Daylighting Intersection			•	•	•	•	•	•	•	•	•	•	•			
Diverters			•	•	•		•	•	•							
Turn Aprons / Mountable Curbs				•		•			•	•	•	•	•			
Flush Medians				•		•			•	•	•	•	•			

KEY

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CA: Commercial Alley
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Figure A13. Complete Streets Best Practice Guidelines

9.8.13. *Street Design Manual, NYC DOT*

Widened sidewalks, curb extensions, and median refuge islands can be used to enhance safety. Bus lanes can be adopted to facilitate transit. Delivery access may be allowed at all times or in off–hours in transit streets, and in off-hours in pedestrian-only streets. Deliveries and pick–up/drop–off can be considered to be assigned in adjacent buildings (New York City Department of Transportation, 2020).

9.8.14. *Complete Street Design Guidelines, Windsor, CA*

Curb extensions should be provided at many intersections to increase the visibility of pedestrians prior to crossing. Bike lanes are provided in cities, and can possibly be provided on the rural areas if a wide shoulder is present. Angled parking is provided only on streets where design speeds are low. Consideration of the width of travel lanes is important when a street has a high percentage of truck traffic, including wider parking lanes for streets with high daily traffic volumes (Whitlock & Weinberger Transportation Inc., 2013).

9.9. Summary of Practices

Complete Streets prioritizes the creation of a safe environment for all users, including pedestrians of all ages and abilities, bicyclists, transit users, emergency responders, freight delivery vehicles, private motor vehicles, and ride-hailing vehicles. This range of users, of course, should be under consideration when cities allocate curb space. Depending on local needs, cities may choose various Complete Streets strategies to manage curb space most effectively. These strategies allow for the safe usage of all components of the transportation network. Depending on the Complete Streets strategy being analyzed, different strategies are recommended. Several guidelines were examined to determine which strategies were most commonly implemented: ITE's Curb Management Guideline, the NACTCO Curbside Management for Improving Transit Reliability, the San Francisco General Plan, the Complete Streets Implementation Action Plan 2.0 from Caltrans, the North Carolina DOT Complete Street Planning and Reliability, the New Haven Complete Street Design Manual, the Complete Street Design of Los Angeles, and the Pasadena Design Guideline to Complete Streets. Table A8 summarizes the strategies, as well as which regional plans have implemented each.

Table A8. Summary of Parking Management Related Strategies in Complete Streets

Strategies	ITEs curb management guideline	NACTCO-curbside management for improving transit reliability	San Francisco general plan	Complete Streets Implementation Action Plan 2.0 (Caltrans)	North Carolina DOT complete street planning and design guidelines	New Haven complete street design manual	Complete street design of Los Angel	Pasadena-Design-Guideline complete street
Flex zones	√	√	√			√	√	√
Using automated enforcement	√	√						
Road diets/width				√				
Moving Loading and Access around the corner	√	√			√		√	
Demand-Based Parking Pricing	√	√	√					
Time limit and time-of-day restriction	√	√						
inclusion of off-street parking	√	√						
Reduced occupancy target	√	√			√			
Priority parking permit for specific zone					√	√		
Angle parking			√	√			√	
Geofencing	√							
Implementing paid access for freight zone (designated commercial zones with limited time)	√	√					√	√
Charging delivery vehicles in peak-time	√	√				√		
Staging zone	√	√						
Wider truck lanes and turning radii			√			√	√	√
Last mile delivery	√	√						
Sidewalk widening, bulb, art and furniture	√		√	√	√	√	√	√
Bus lane, and bus queue jump lane, bus priority (Median Bus Lane / Busway)	√	√	√	√	√		√	
Bus boarding islands or bulbs (Median Bus Boarding Island	√	√	√	√	√		√	
Bike-transit/taxi integration			√					
Protect, build bike lane	√		√	√	√	√	√	
Biking storage management	√		√		√	√		√

Sources: (Tomuta, 2011; Litman, 2015; GUIDE, 2019)

10. APPENDIX B. Residential Area

10.1. Searching for On-Street Parking and Off-Street Availability

10.1.1. Vehicle Kilometers Traveled Results

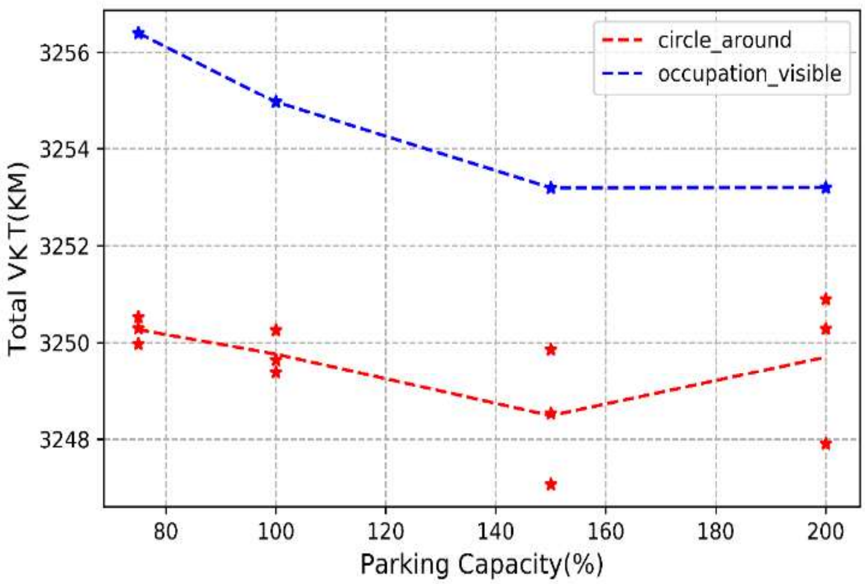

Figure B14. Residential – Parking Search - VKT Results

10.1.2. Travel Time Results

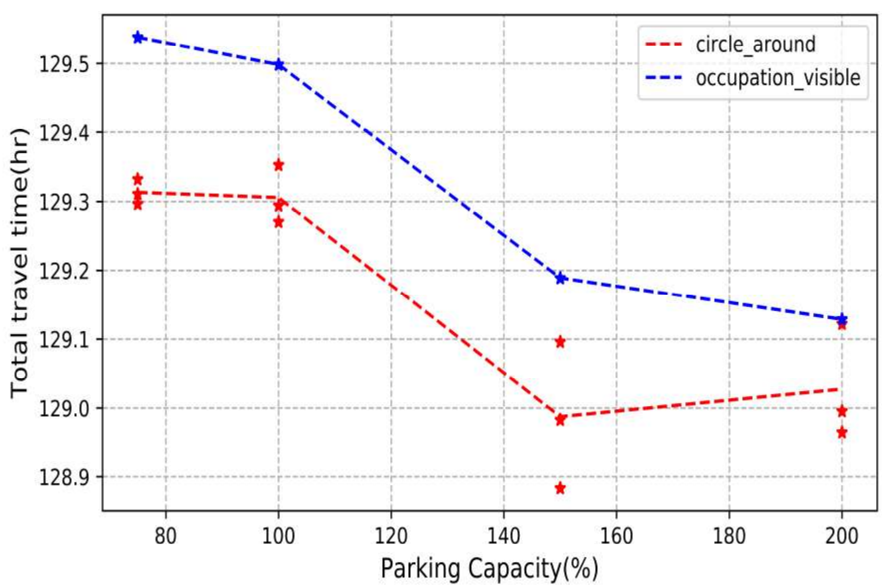

Figure B15. Residential – Parking Search – Travel Time Results

10.1.3. Emissions Results

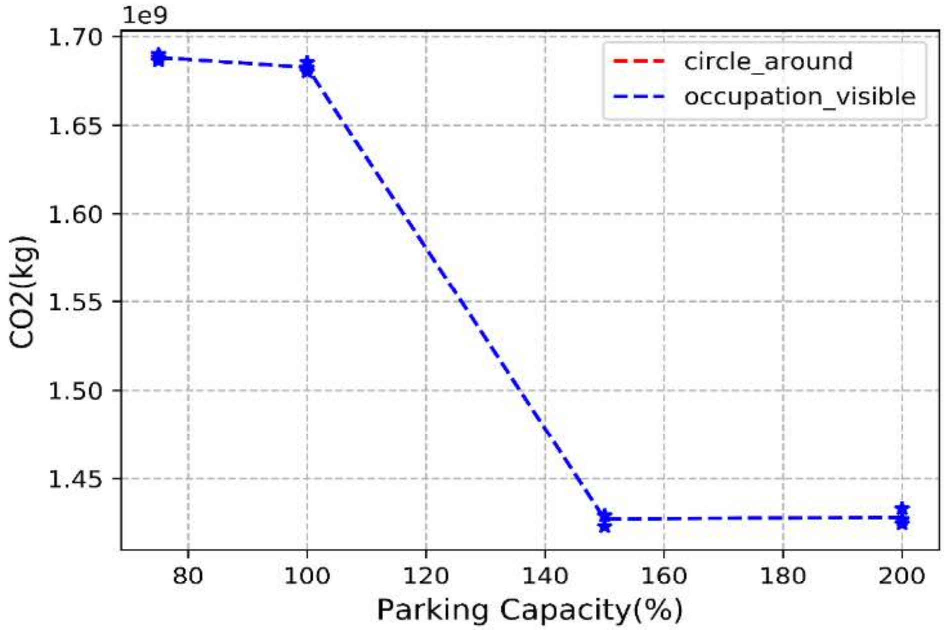

Figure B16. Residential – Parking Search – Emissions Results

10.1.4. Queue Results

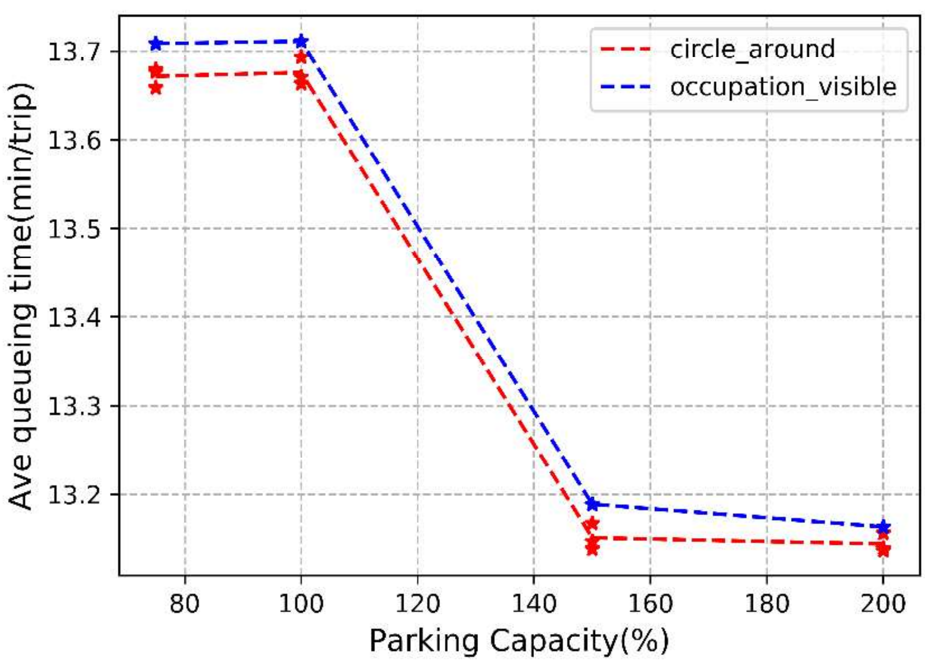

Figure B17. Residential – Parking Search – Queue Time Results

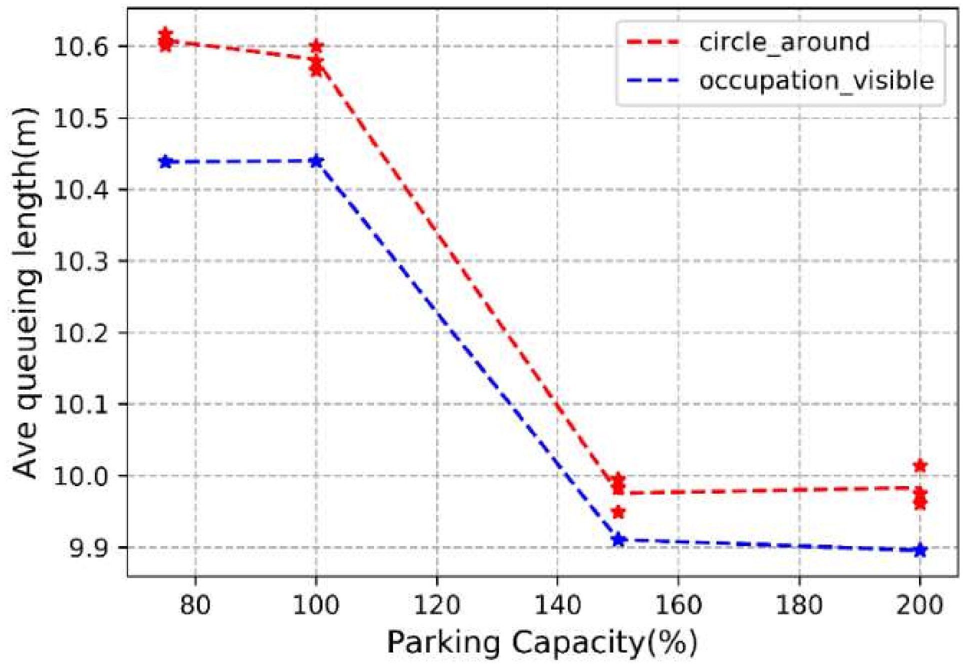

Figure B18. Residential – Parking Search – Queue Length Results

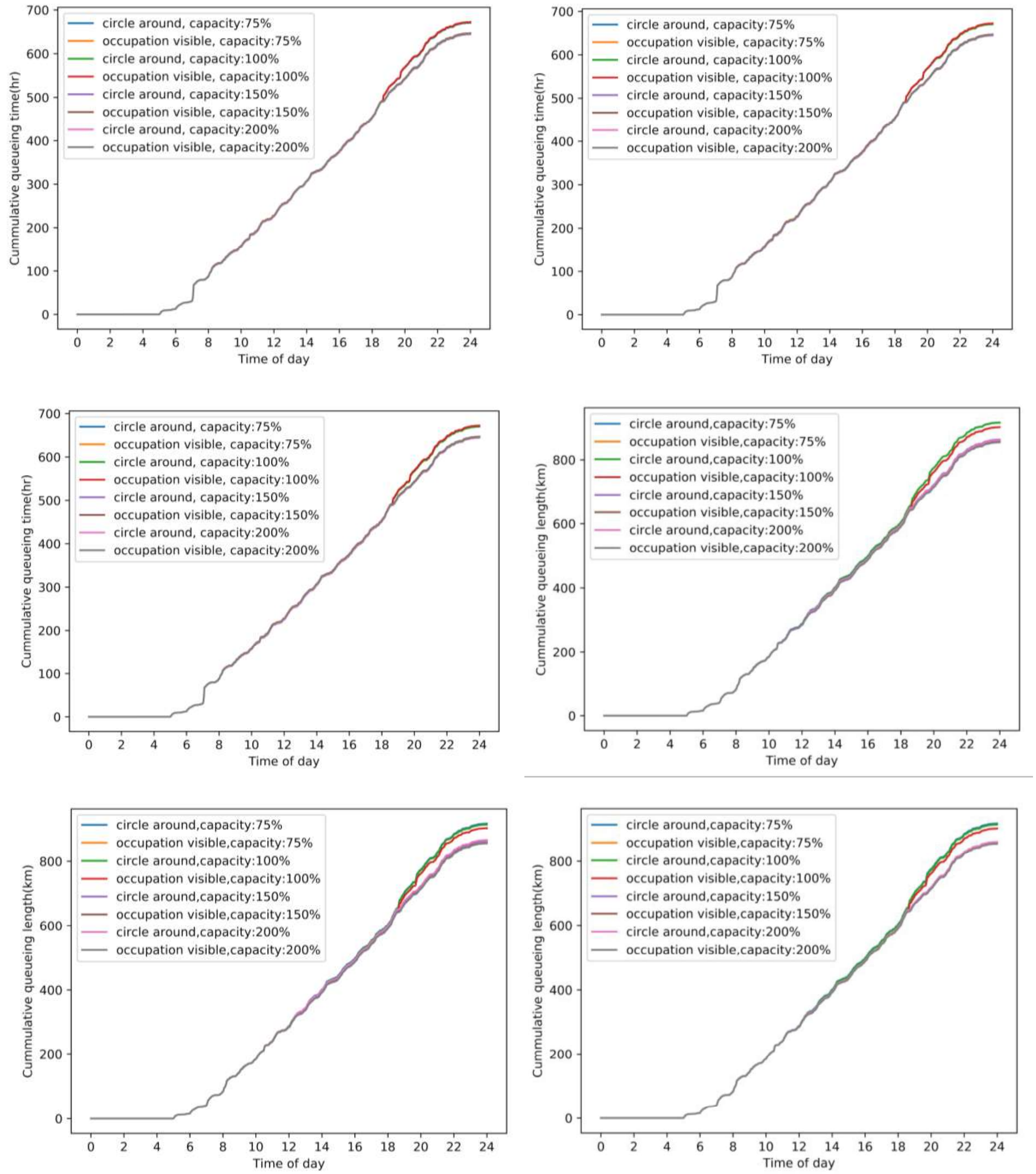

Figure B19. Residential – Parking Search – Queue Cumulative Length Results

10.2. Designated Loading and Unloading areas

10.2.1. Vehicle Kilometers Traveled Results

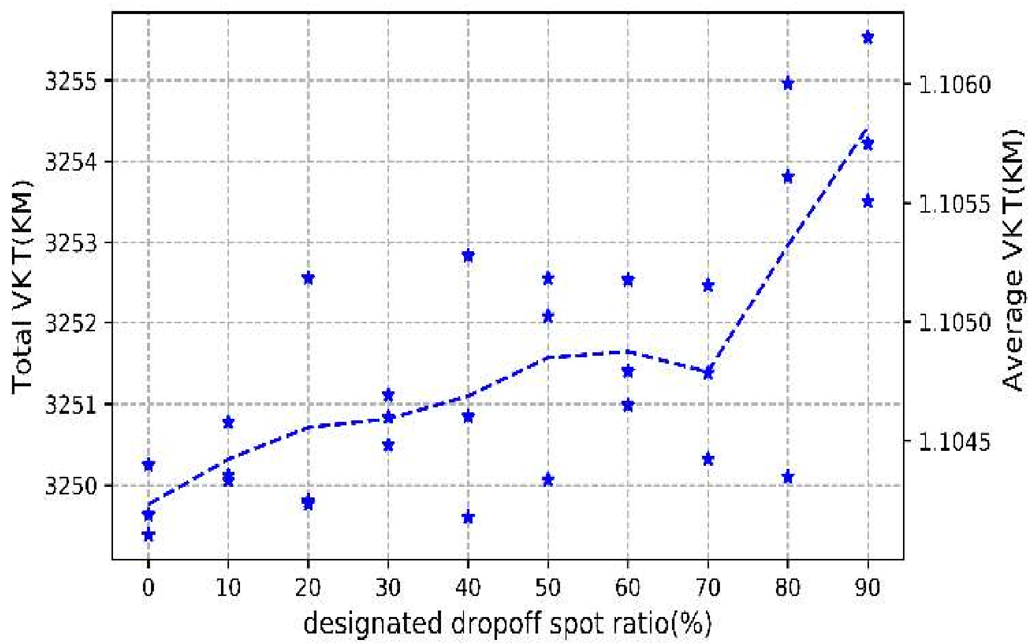

Figure B20. Residential – Designated Parking – VKT Results

10.2.2. Travel Time Results

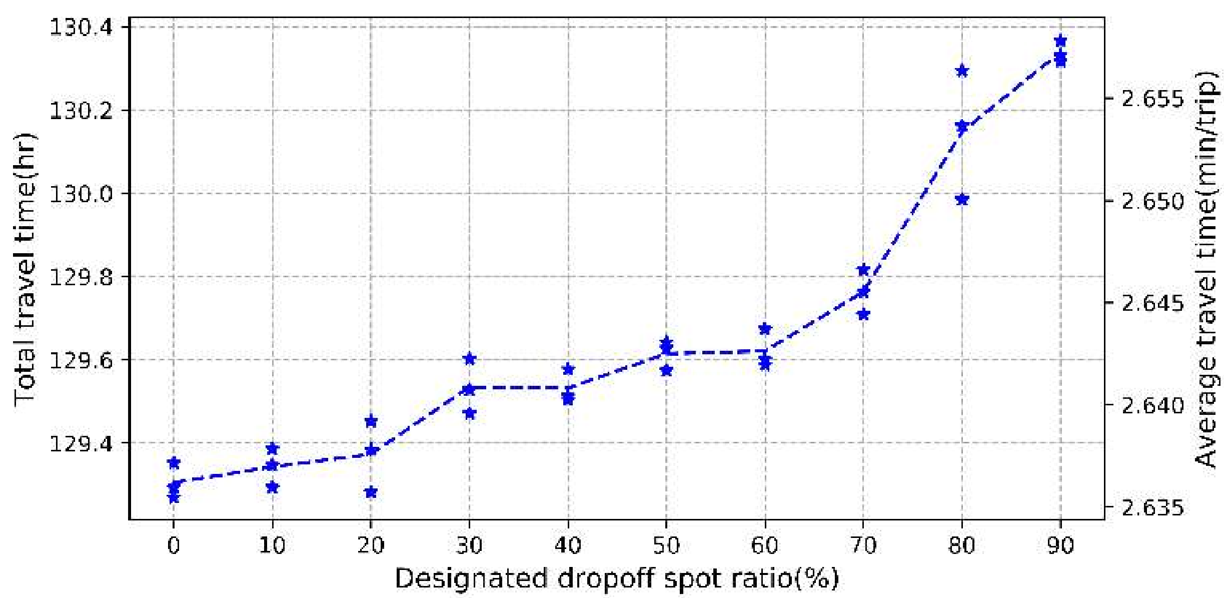

Figure B21. Residential – Designated Parking – Travel Time Results

10.2.3. Emissions Results

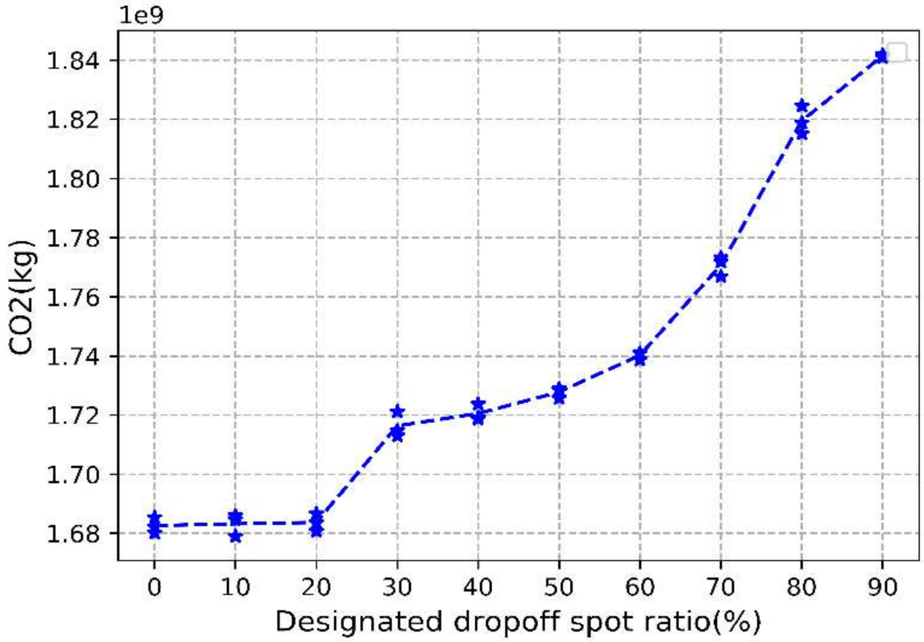

Figure B22. Residential – Designated Parking – Emissions Results

10.2.4. Queue Results

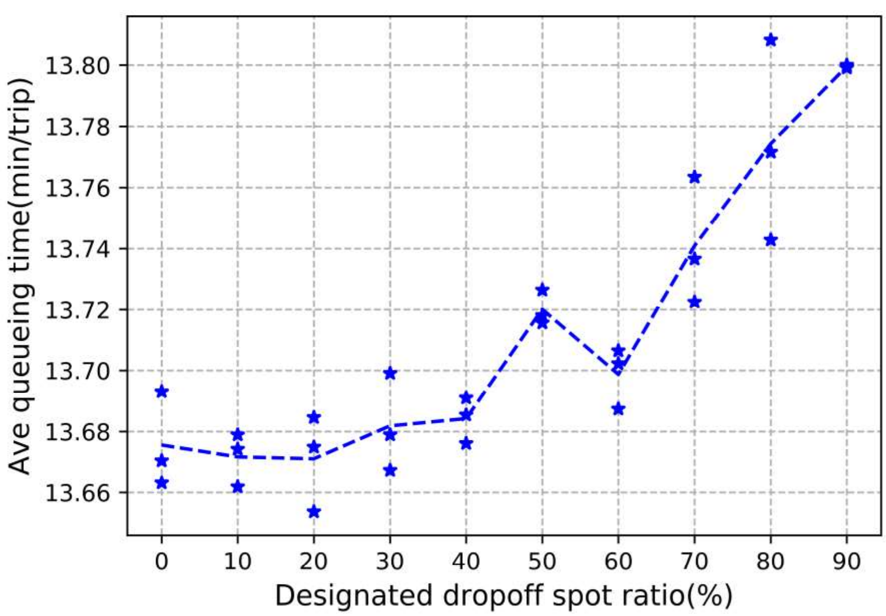

Figure B23. Residential – Designated Parking – Queue Time Results

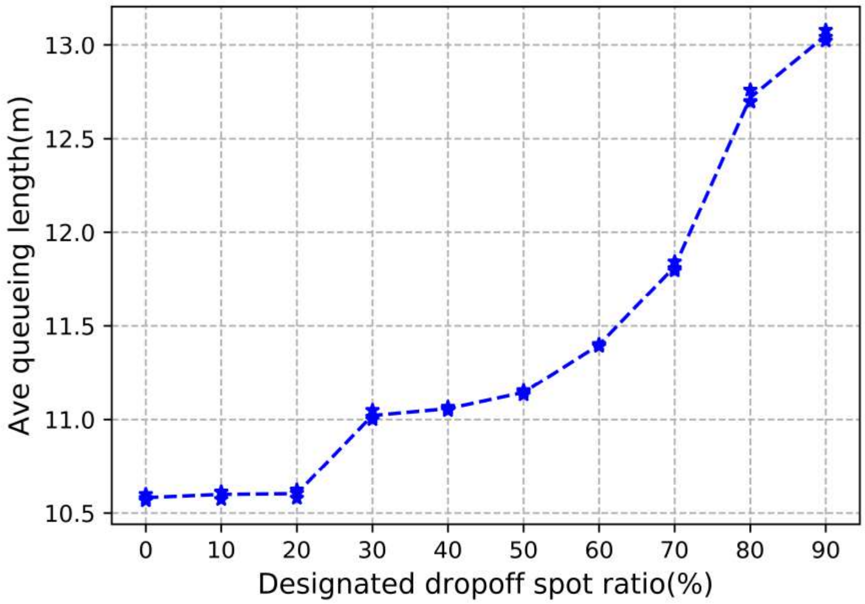

Figure B24. Residential – Designated Parking – Queue Length Results

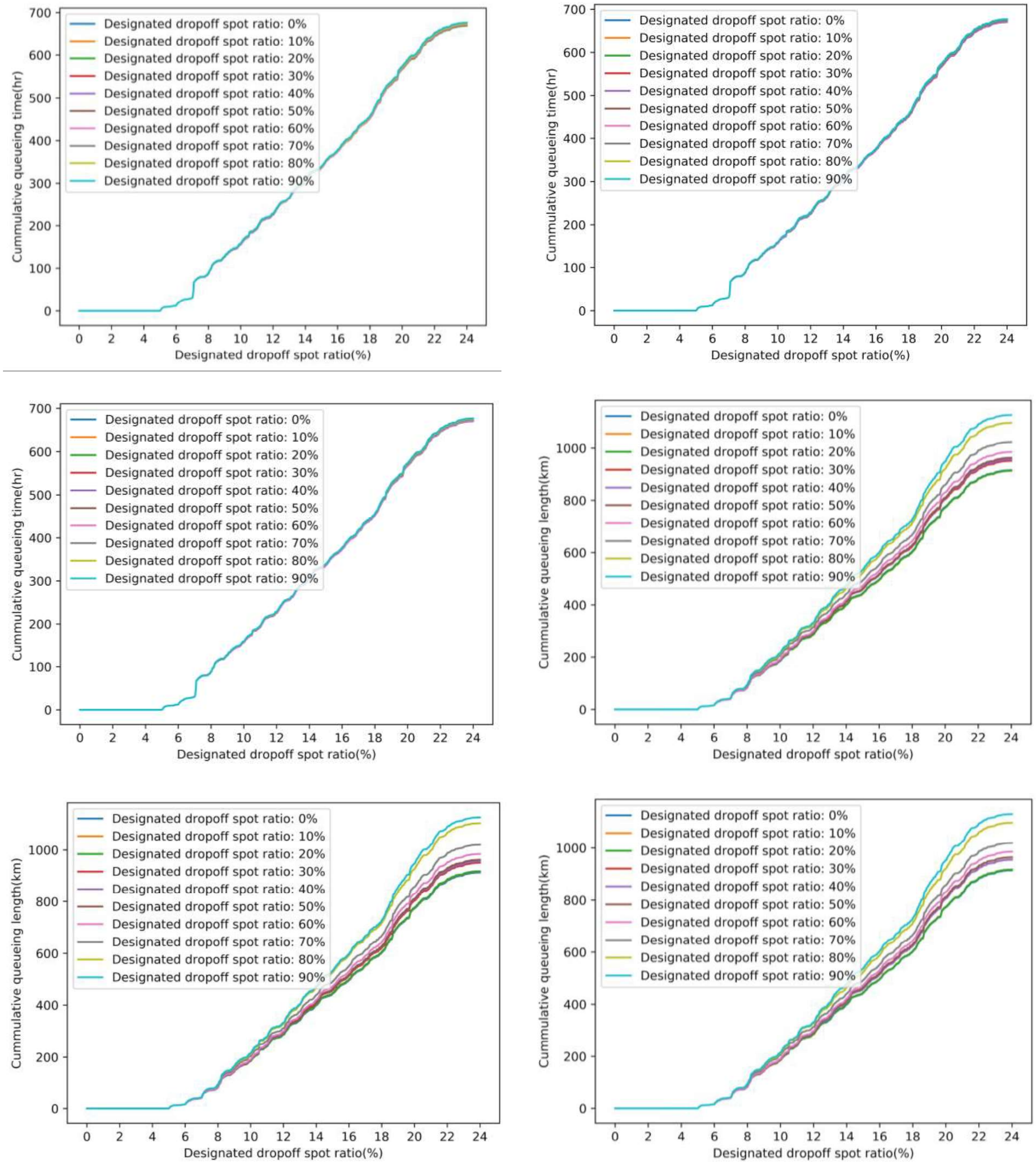

Figure B25. Residential – Designated Parking – Queue Cumulative Length Results

10.3. Parking Time Limits

10.3.1. Vehicle Kilometers Traveled results

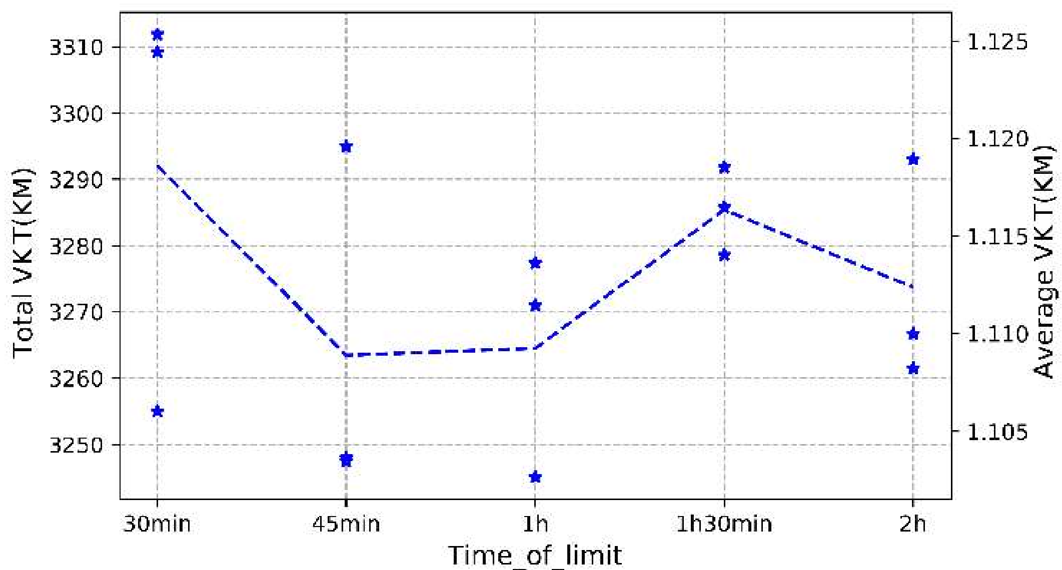

Figure B26. Residential – Parking Time Limits – VKT Results

10.3.2. Travel Time Results

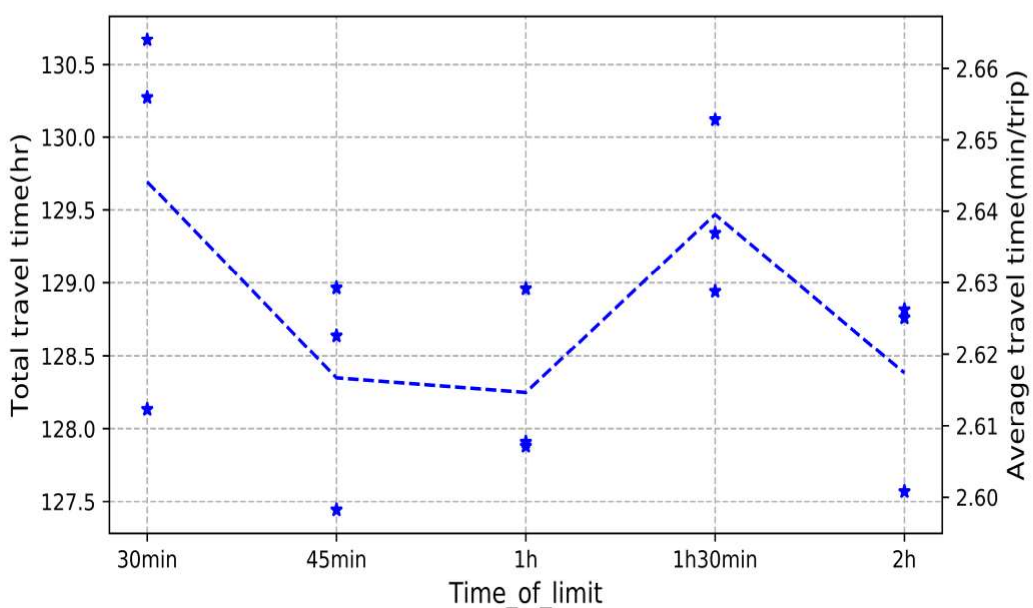

Figure B27. Residential – Parking Time Limits – Travel Time Results

10.3.3. Emissions Results

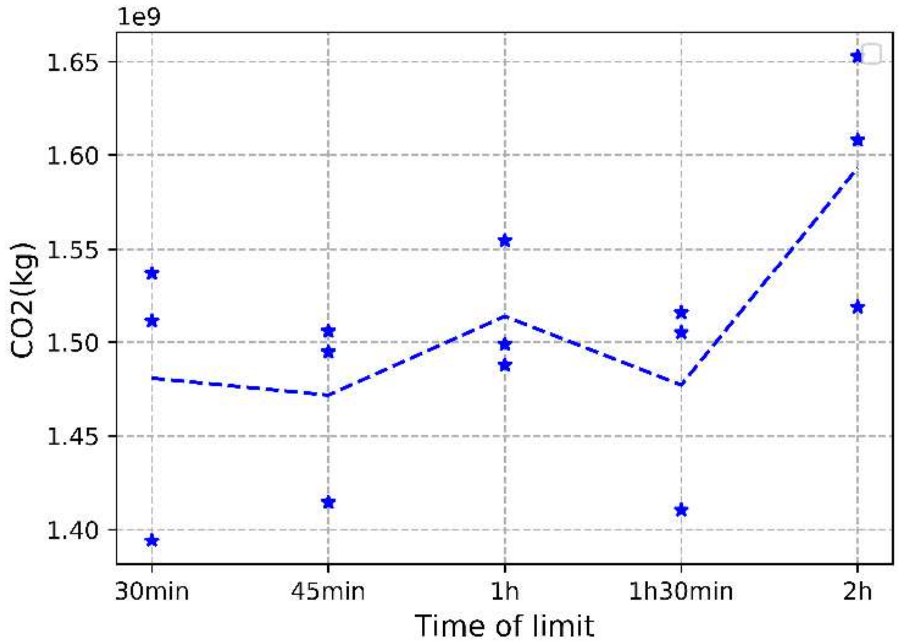

Figure B28. Residential – Parking Time Limits – Emissions Results

10.3.4. Queue Results

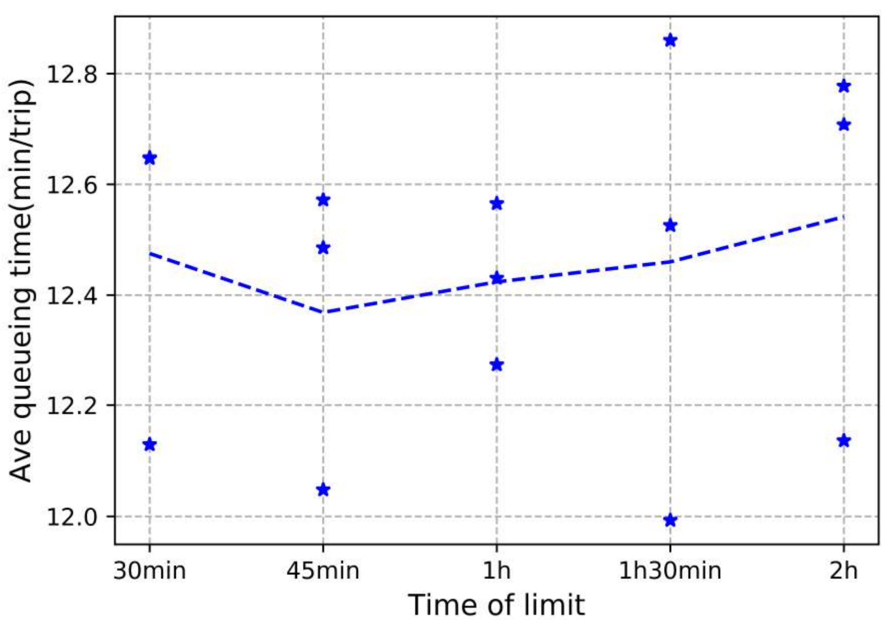

Figure B29. Residential – Parking Time Limits – Queue Times Results

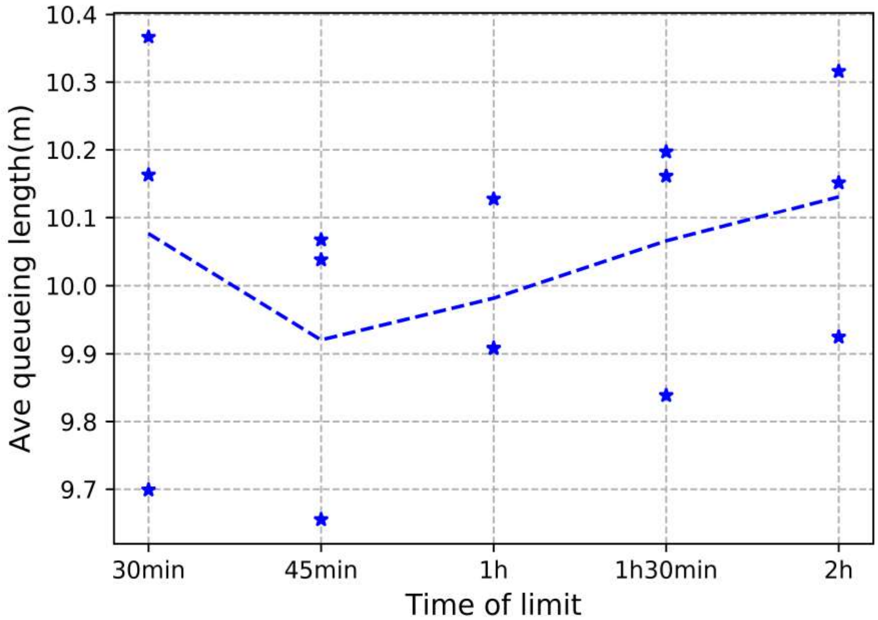

Figure B30. Residential – Parking Time Limits – Queue Length Results

10.4. Double Parking

10.4.1. Vehicle Kilometers Traveled Results

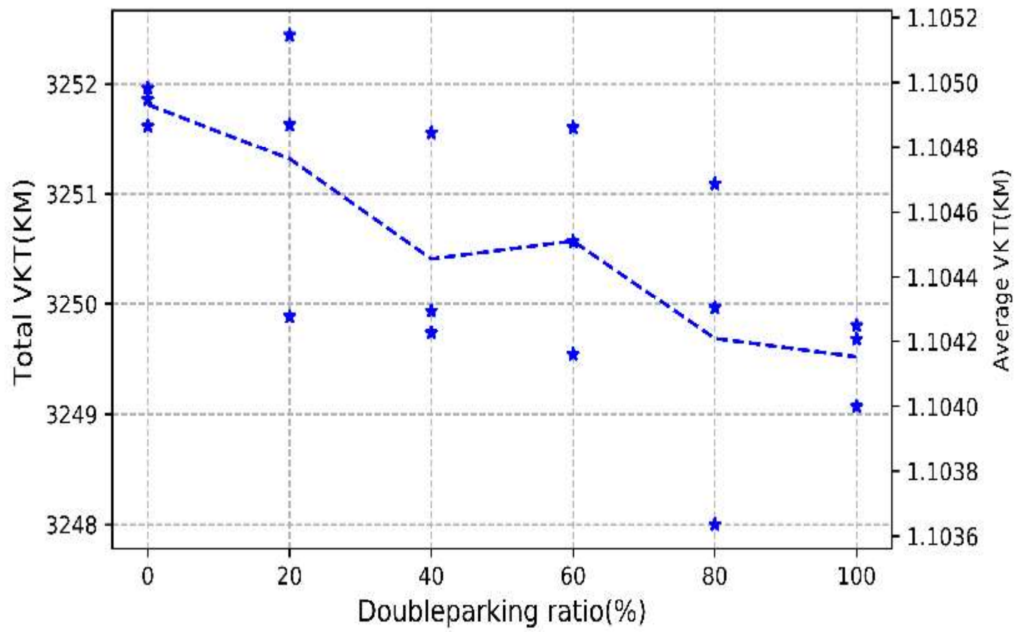

Figure B31. Residential – Double Parking – VKT Results

10.4.2. Travel Time Results

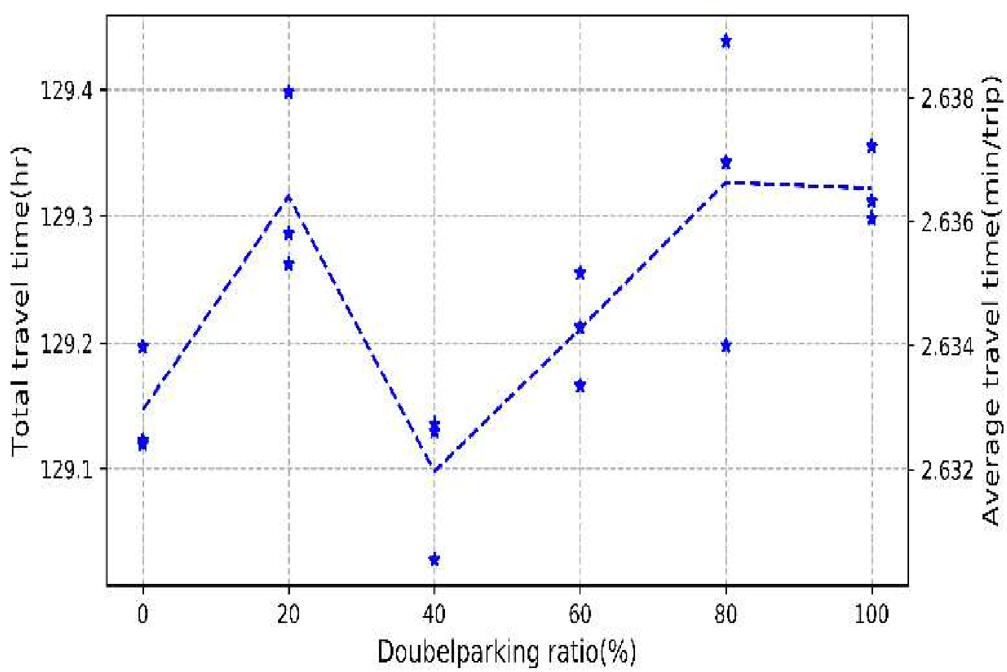

Figure B32. Residential – Double Parking – Travel Time Results

10.4.3. Emissions Results

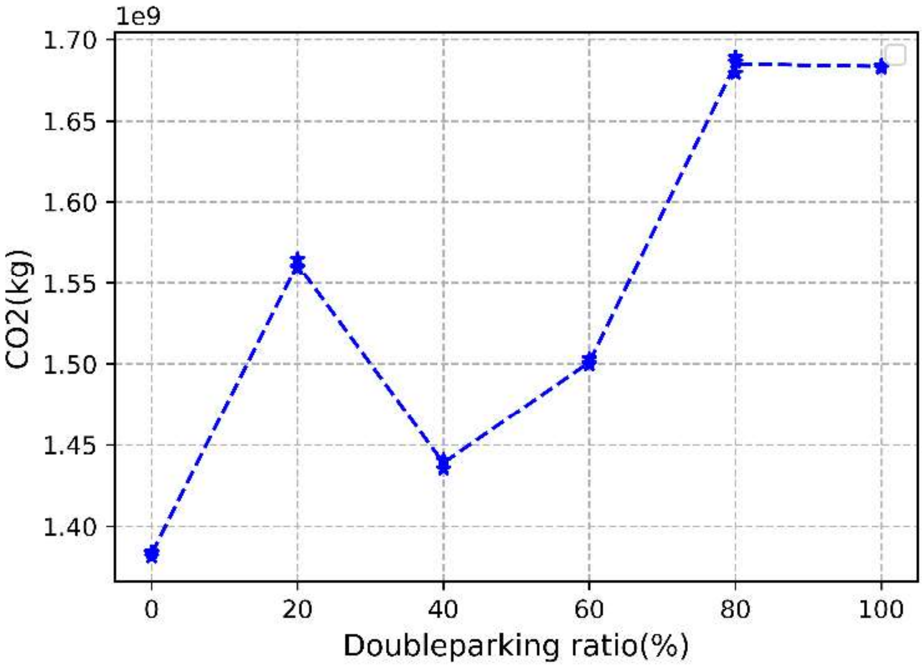

Figure B33. Residential – Double Parking – Emissions Results

10.4.4. Queue Results

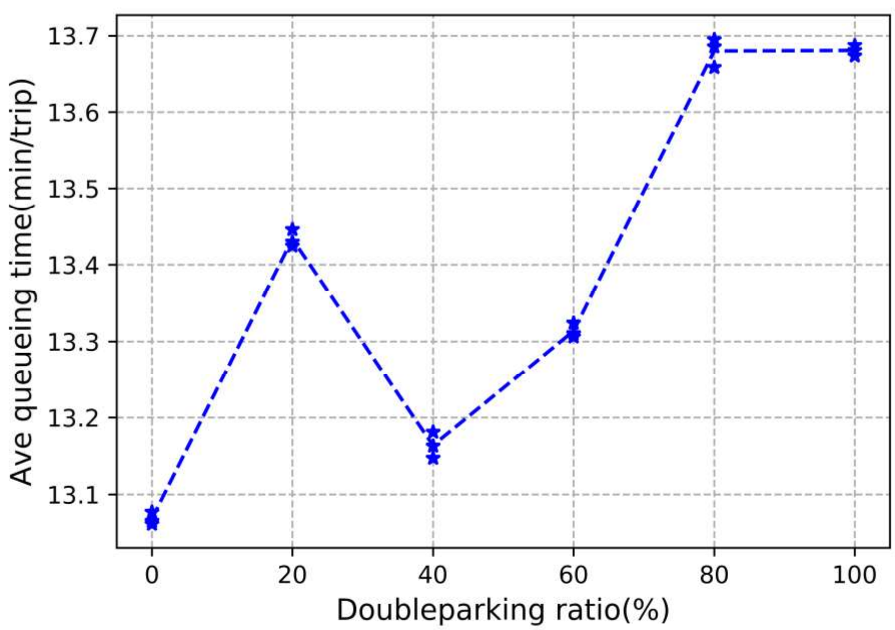

Figure B34. Residential – Double Parking – Queue Time Results

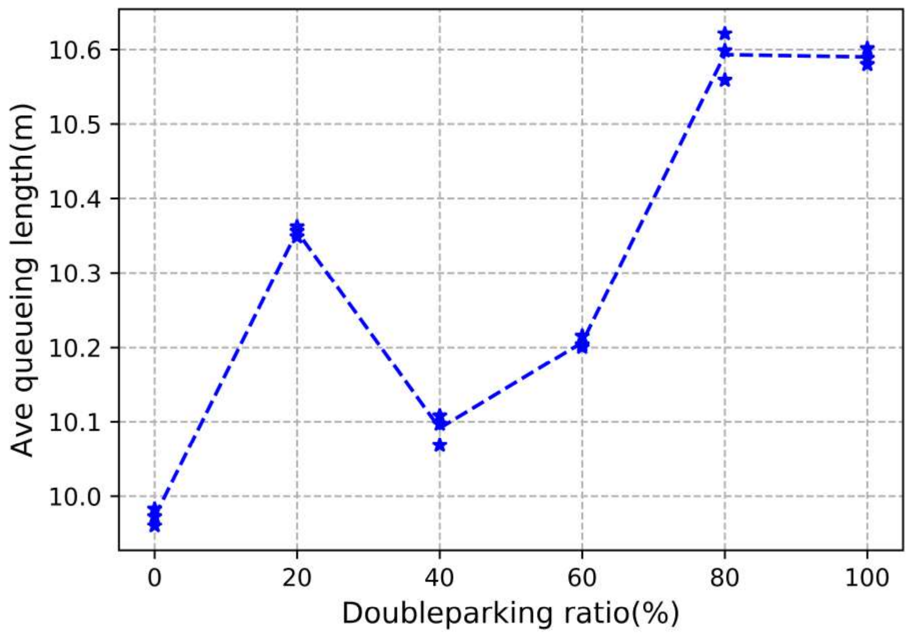

Figure B35. Residential – Double Parking – Queue Length Results

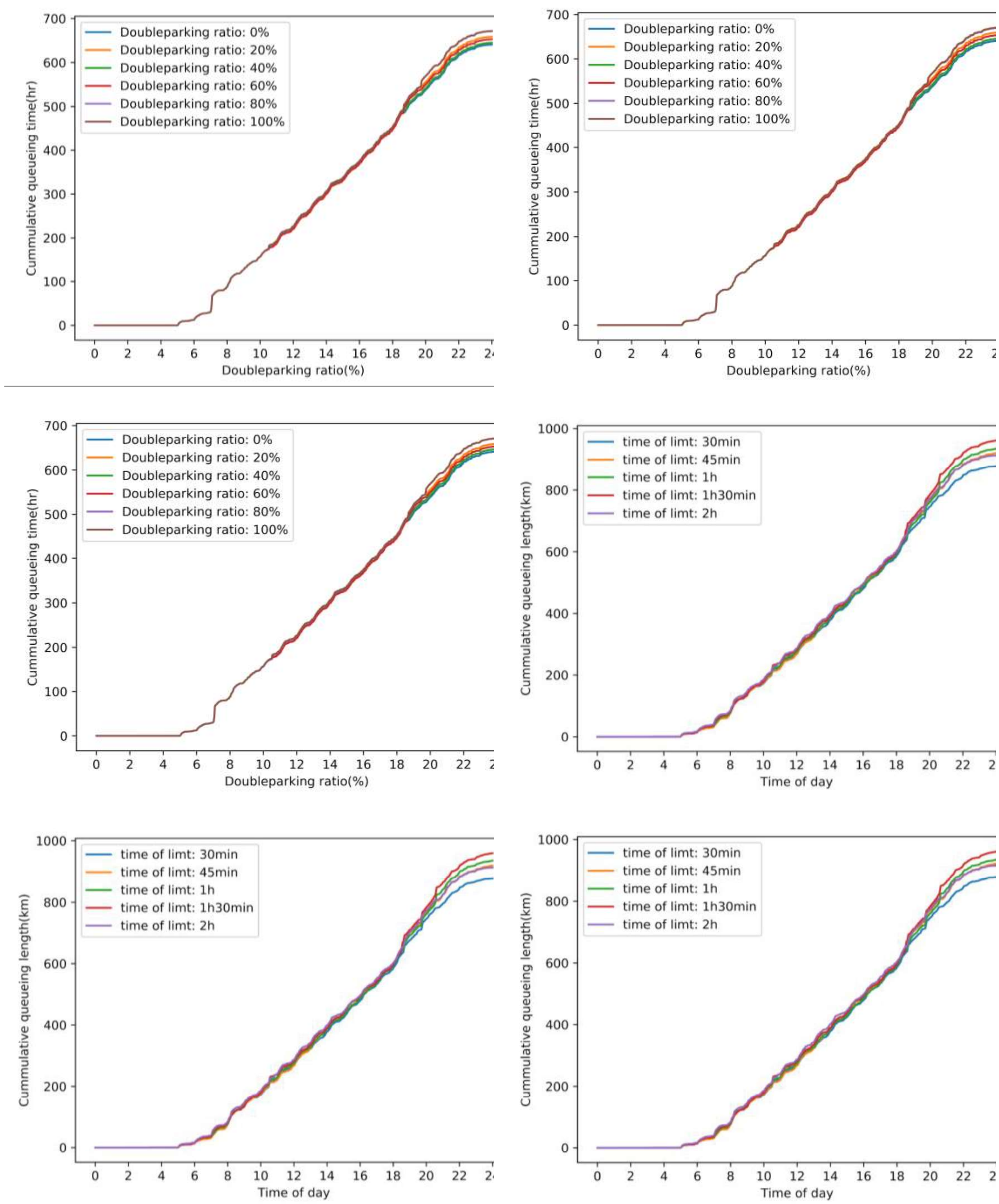

Figure B36. Residential – Double Parking – Queue Cumulative Length Results

11. APPENDIX C. Mixed-use Area

11.1. Searching for on-street parking and off-street availability

11.1.1. Vehicle Kilometers Traveled Results

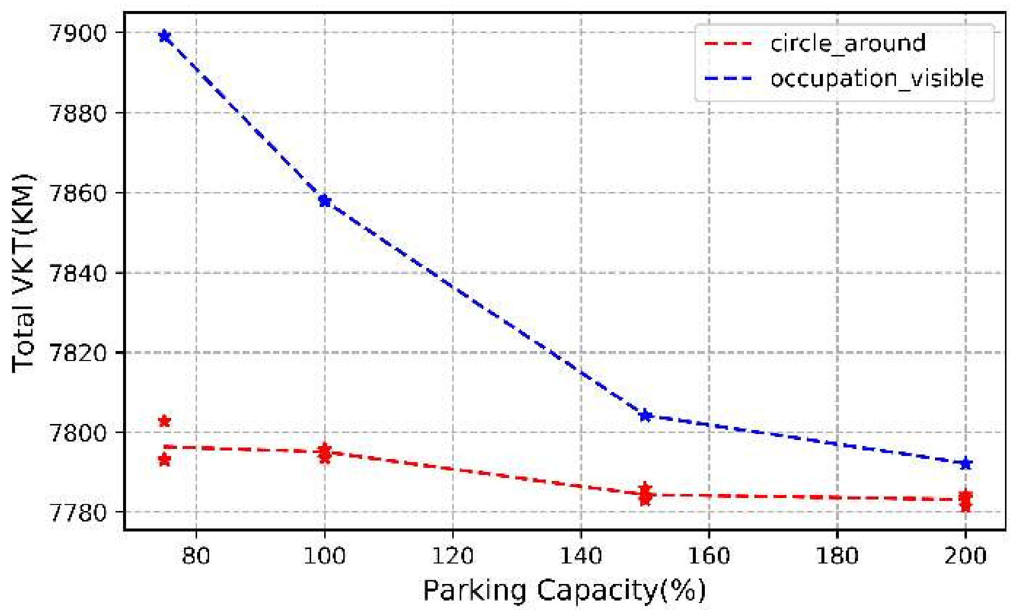

Figure C37. Mixed-use – Parking Search – VKT Results

11.1.2. Travel Time Results

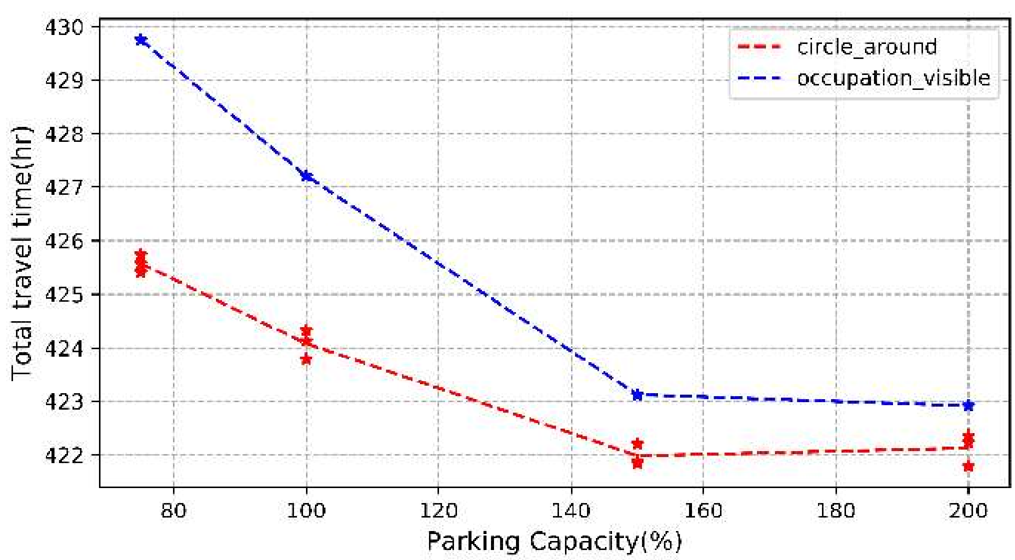

Figure C38. Mixed-use – Parking Search – Travel Time Results

11.1.3. Emissions Results

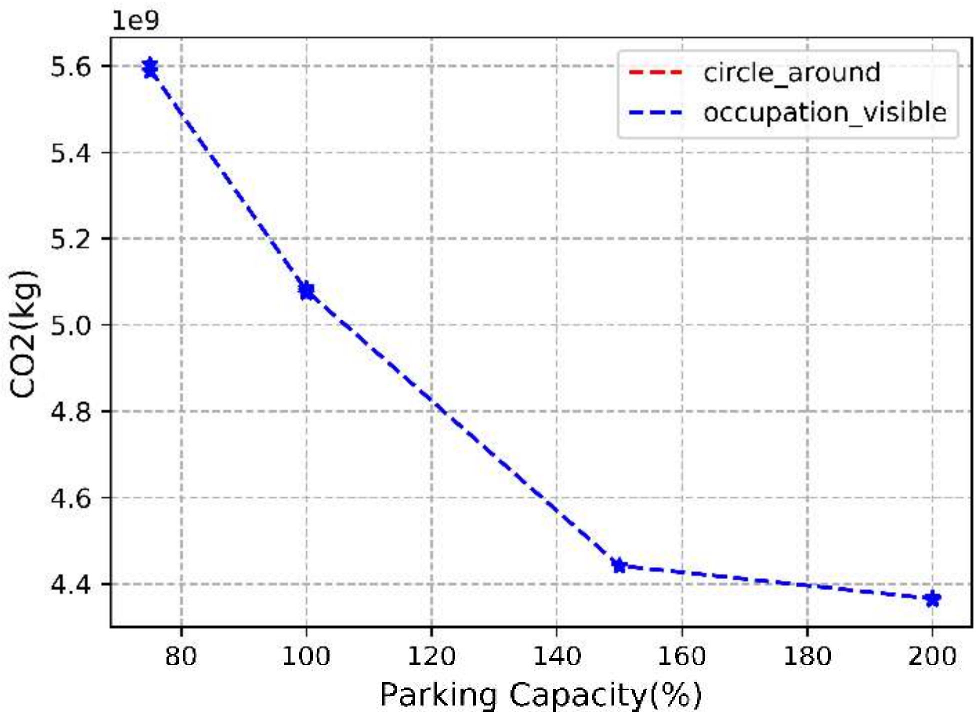

Figure C39. Mixed-use – Parking Search – Emissions Results

11.1.4. Queue Results

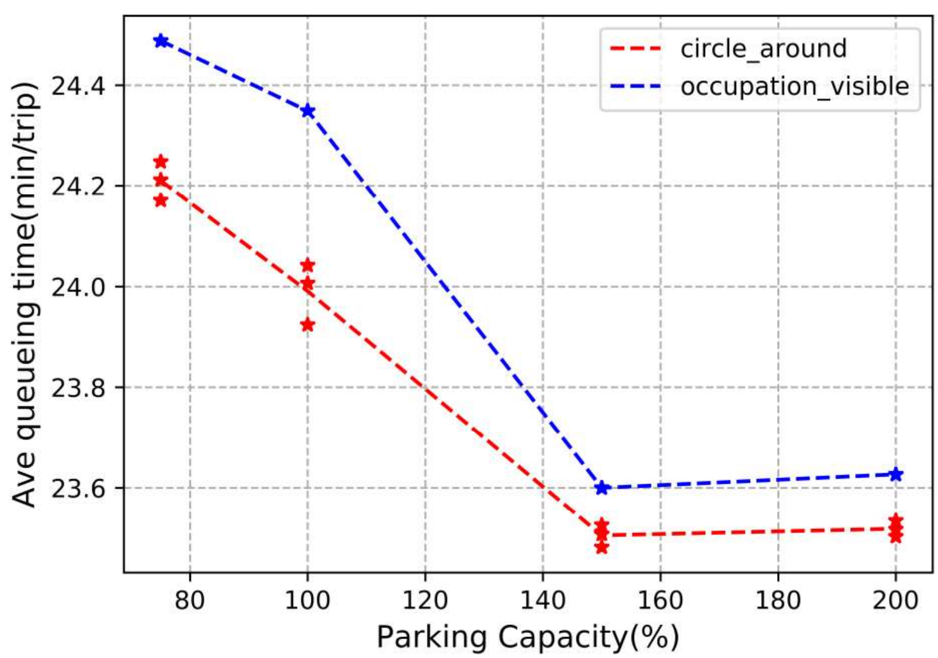

Figure C40. Mixed-use – Parking Search – Queue Times Results

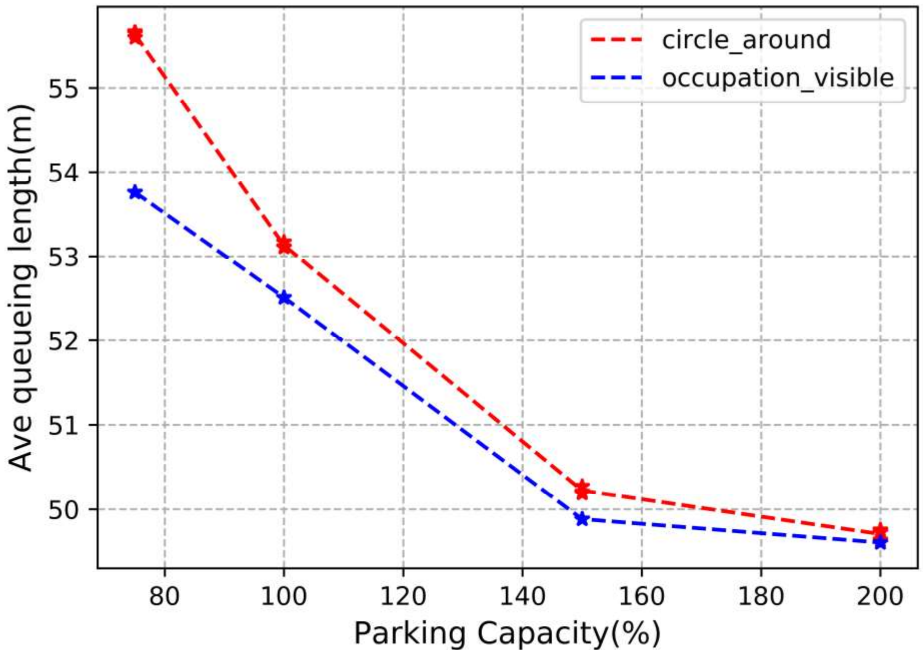

Figure C41. Mixed-use – Parking Search – Queue Length Results

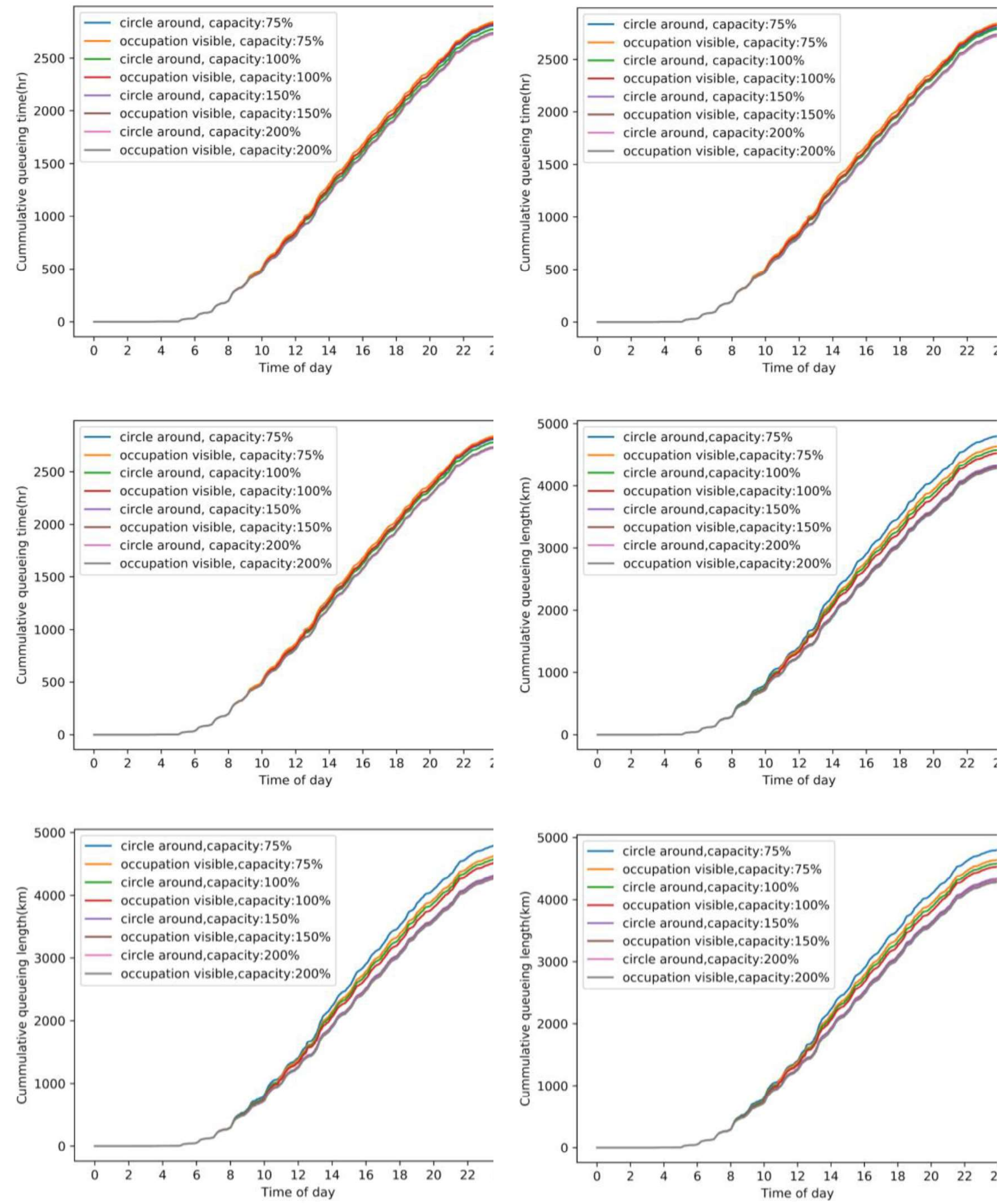

Figure C42. Mixed-use – Parking Search – Queue Cumulative Length Results

11.2. Designated loading and unloading areas

11.2.1. Vehicle Kilometers Traveled Results

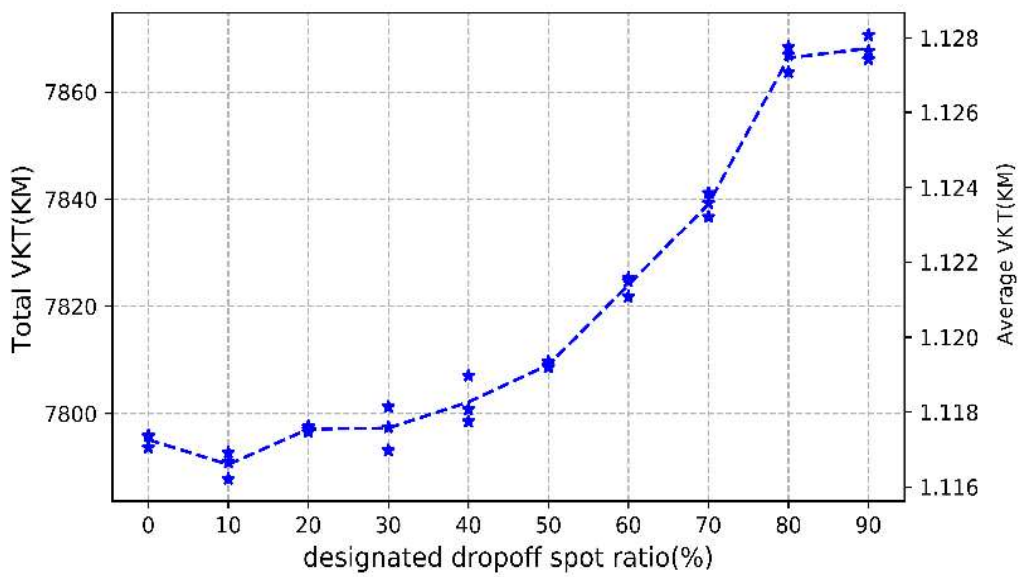

Figure C43. Mixed-use – Designated Parking – VKT Results

11.2.2. Travel Time Results

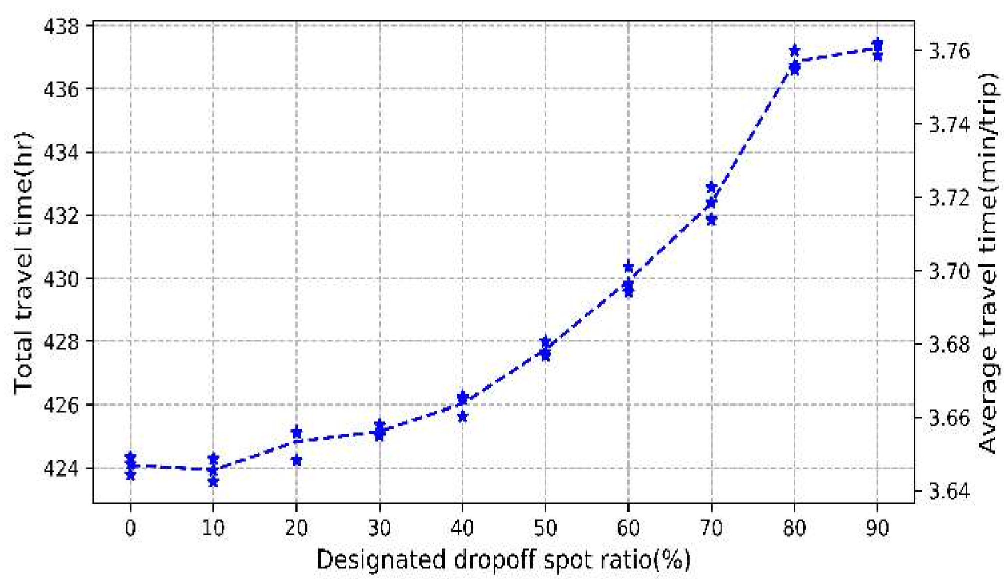

Figure C44. Mixed-use – Designated Parking – Travel Time Results

11.2.3. Emissions Results

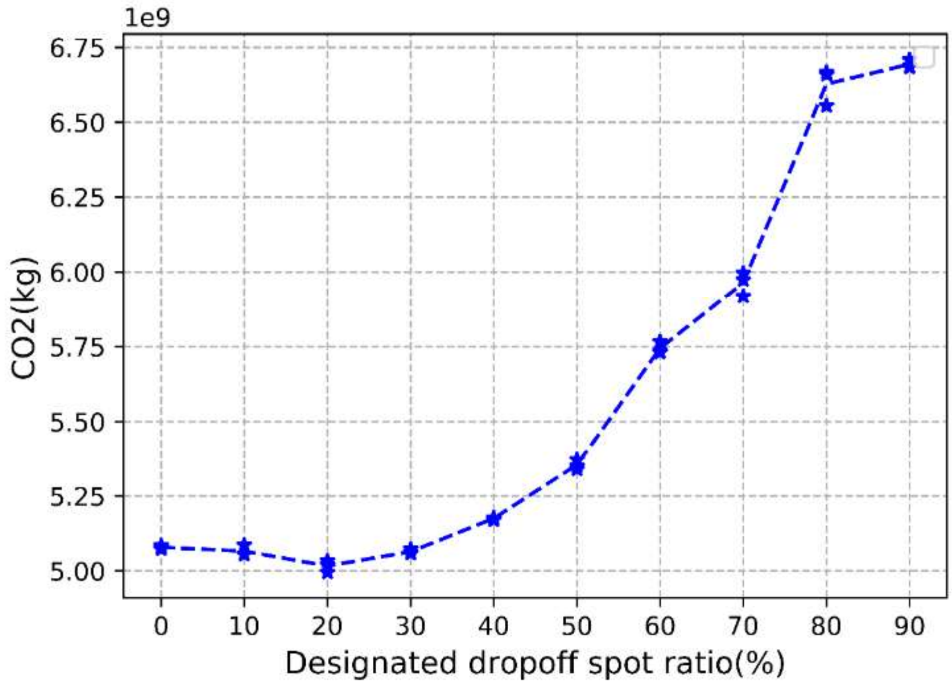

Figure C45. Mixed-use – Designated Parking – Emissions Results

11.2.4. Queue Results

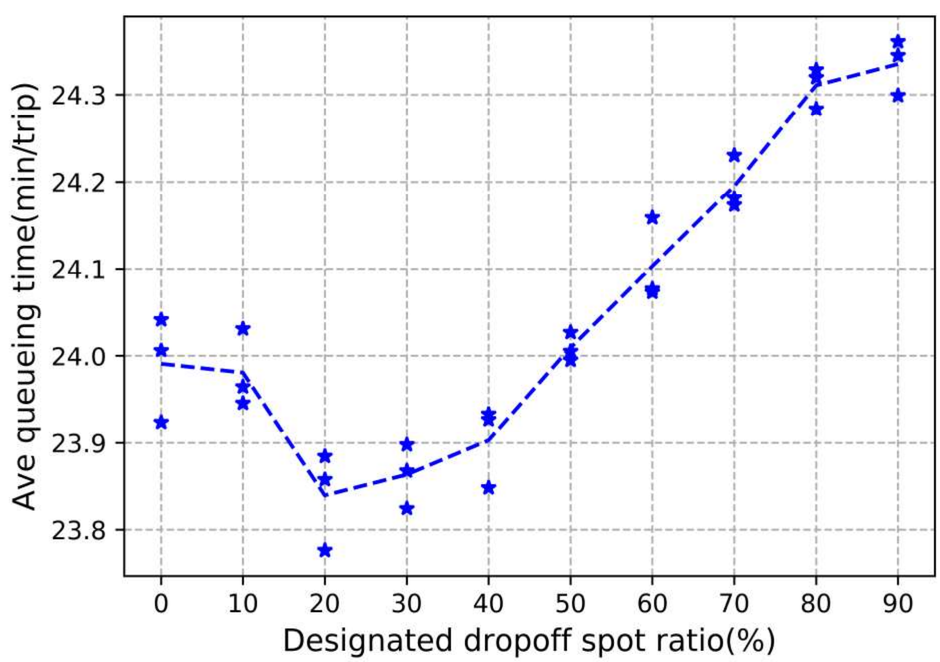

Figure C46. Mixed-use – Designated Parking – Queue Times Results

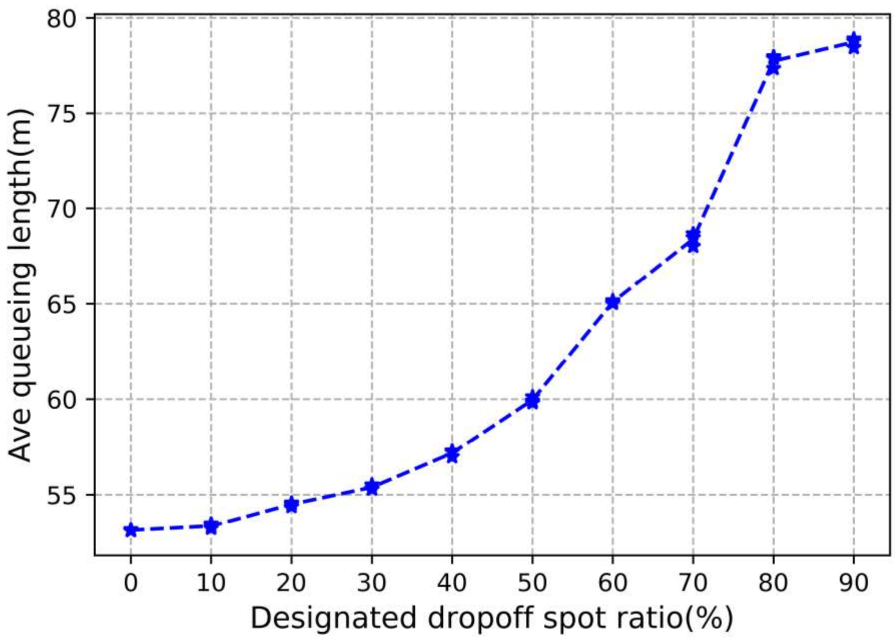

Figure C47. Mixed-use – Designated Parking – Queue Length Results

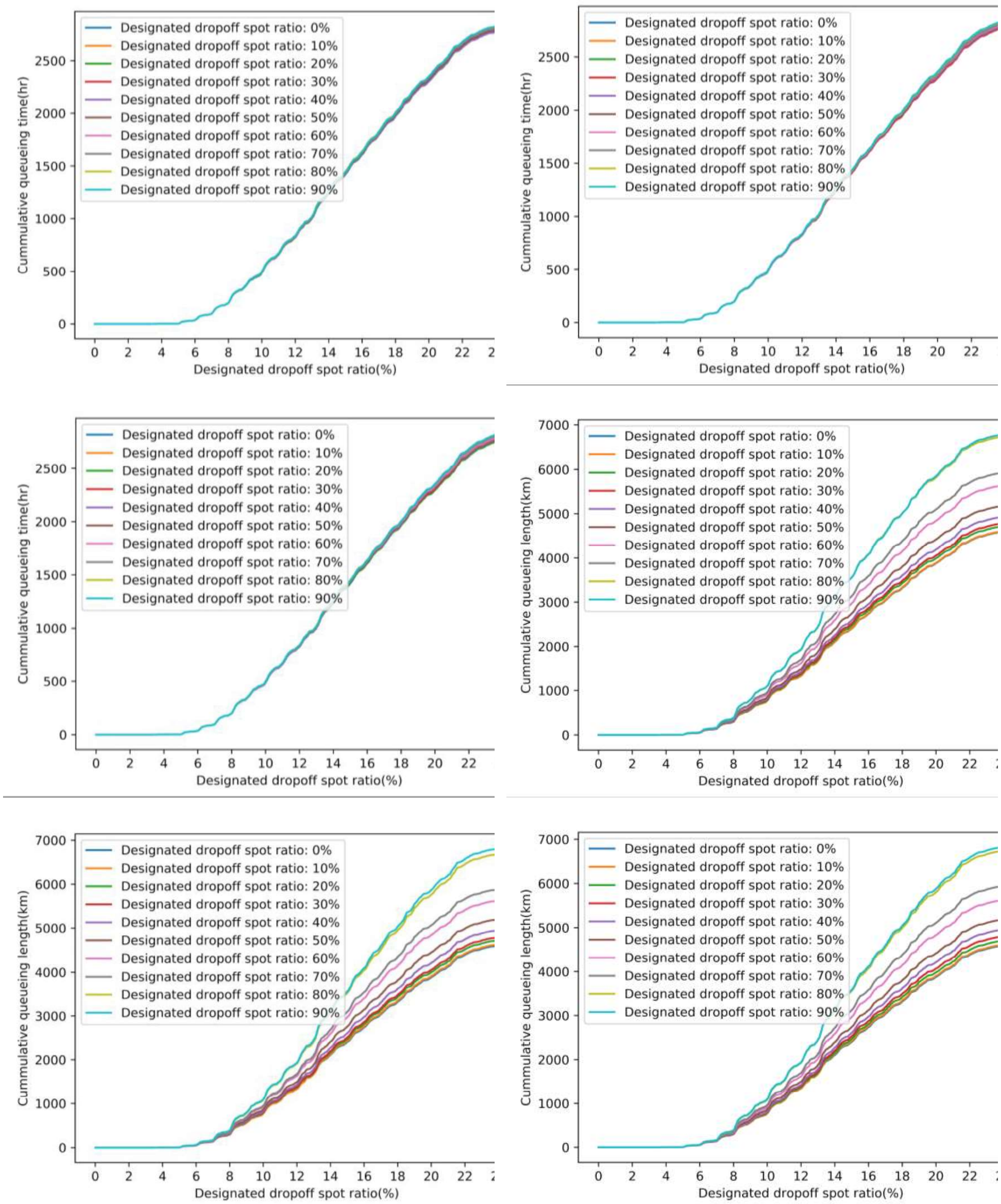

Figure C48. Mixed-use – Designated Parking – Queue Cumulative Length Results

11.3. Parking Time Limits

11.3.1. Vehicle Kilometers Traveled Results

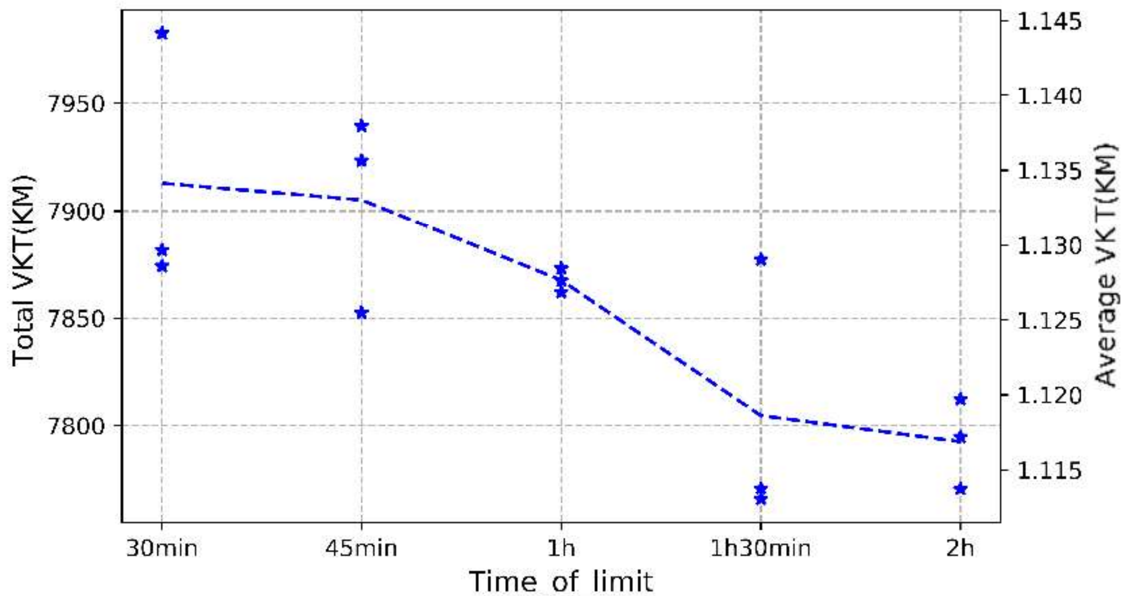

Figure C49. Mixed-use – Parking Time Limits – VKT Results

11.3.2. Travel Time Results

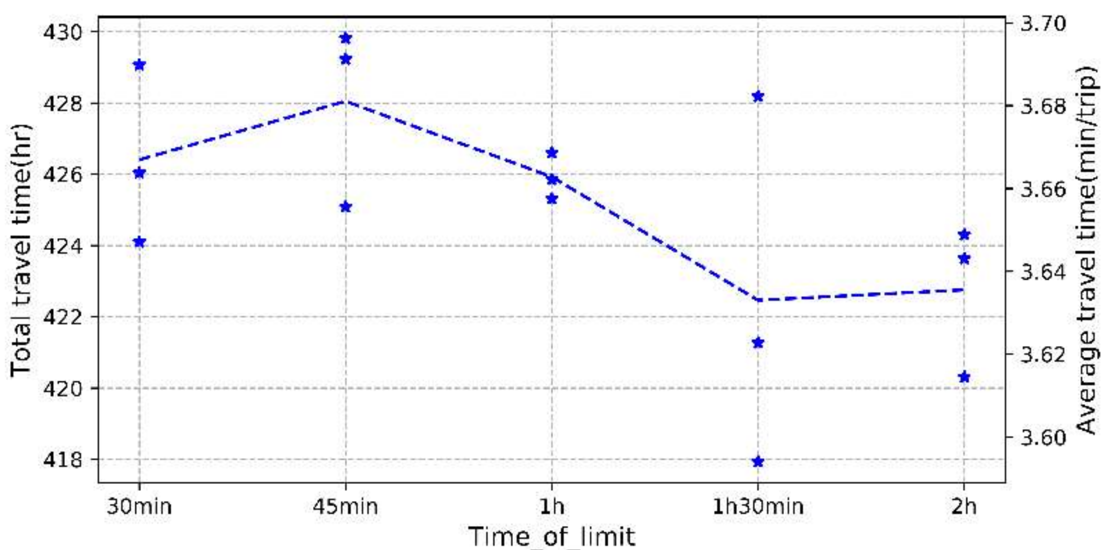

Figure C50. Mixed-use – Parking Time Limits – Travel Times Results

11.3.3. Emissions Results

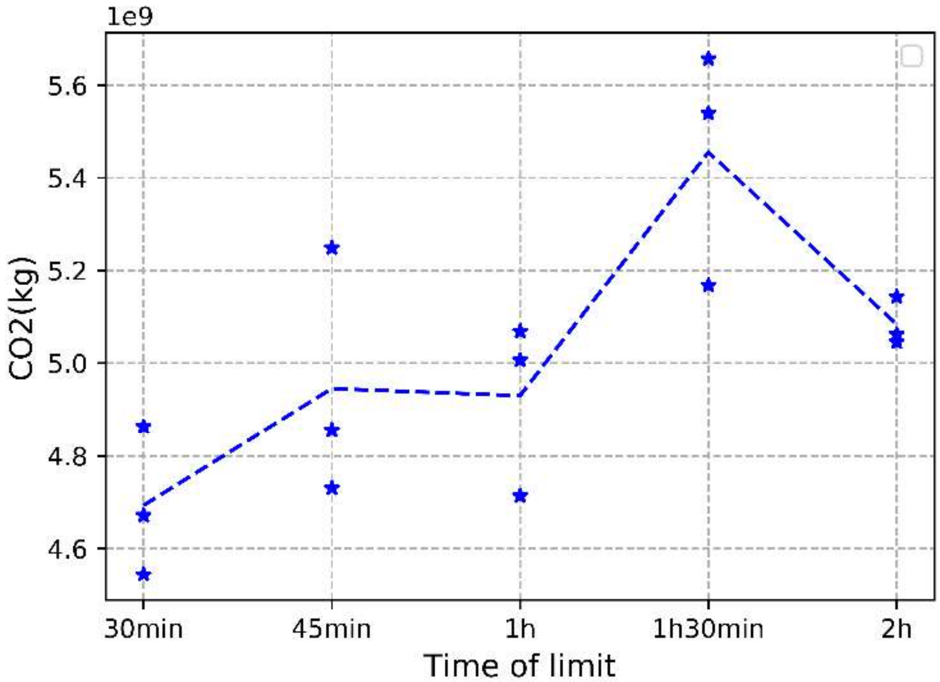

Figure C51. Mixed-use – Parking Time Limits – Emissions Results

11.3.4. Queue Results

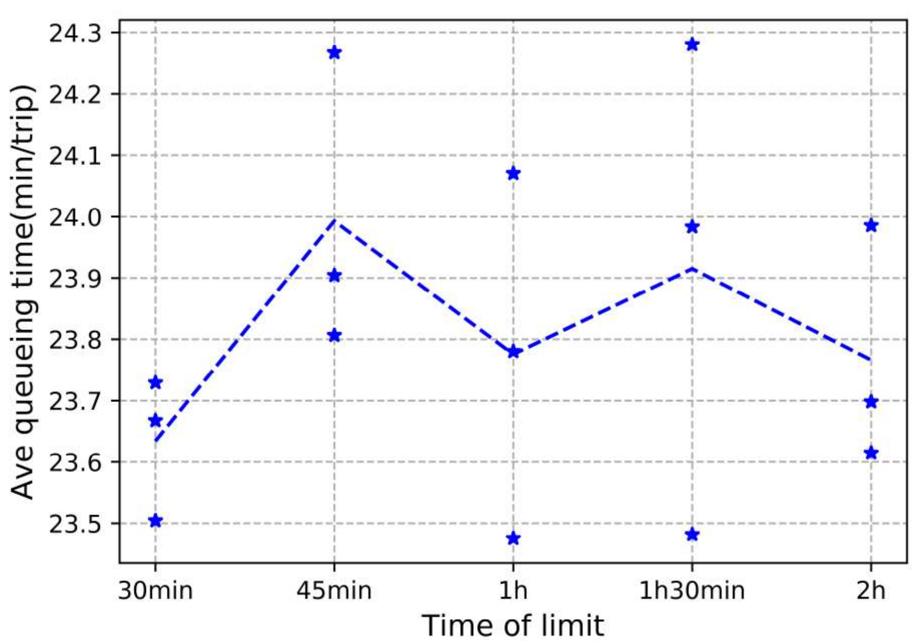

Figure C52. Mixed-use – Parking Time Limits – Queue Times Results

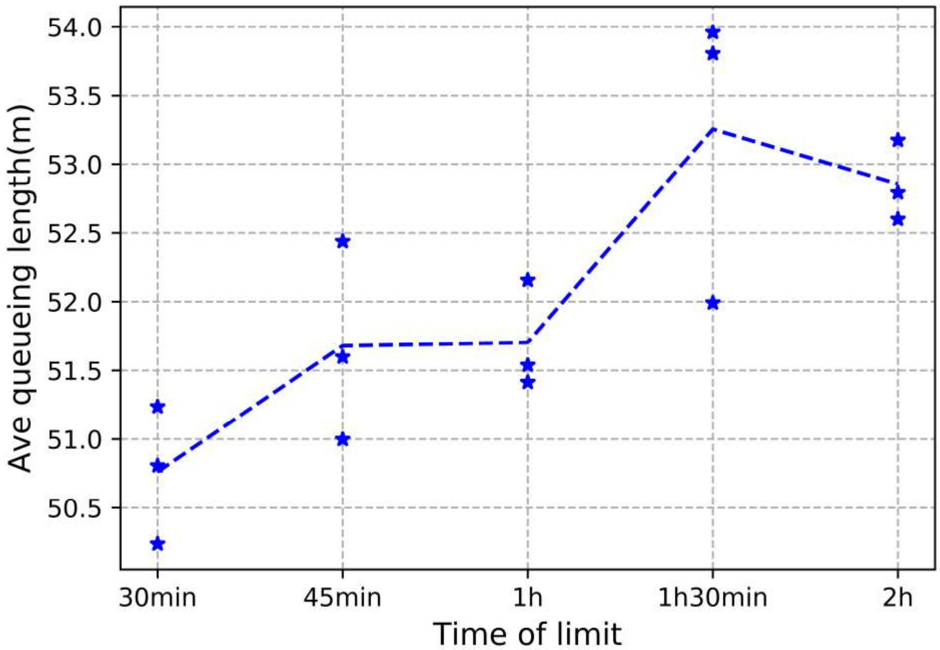

Figure C53. Mixed-use – Parking Time Limits – Queue Length Results

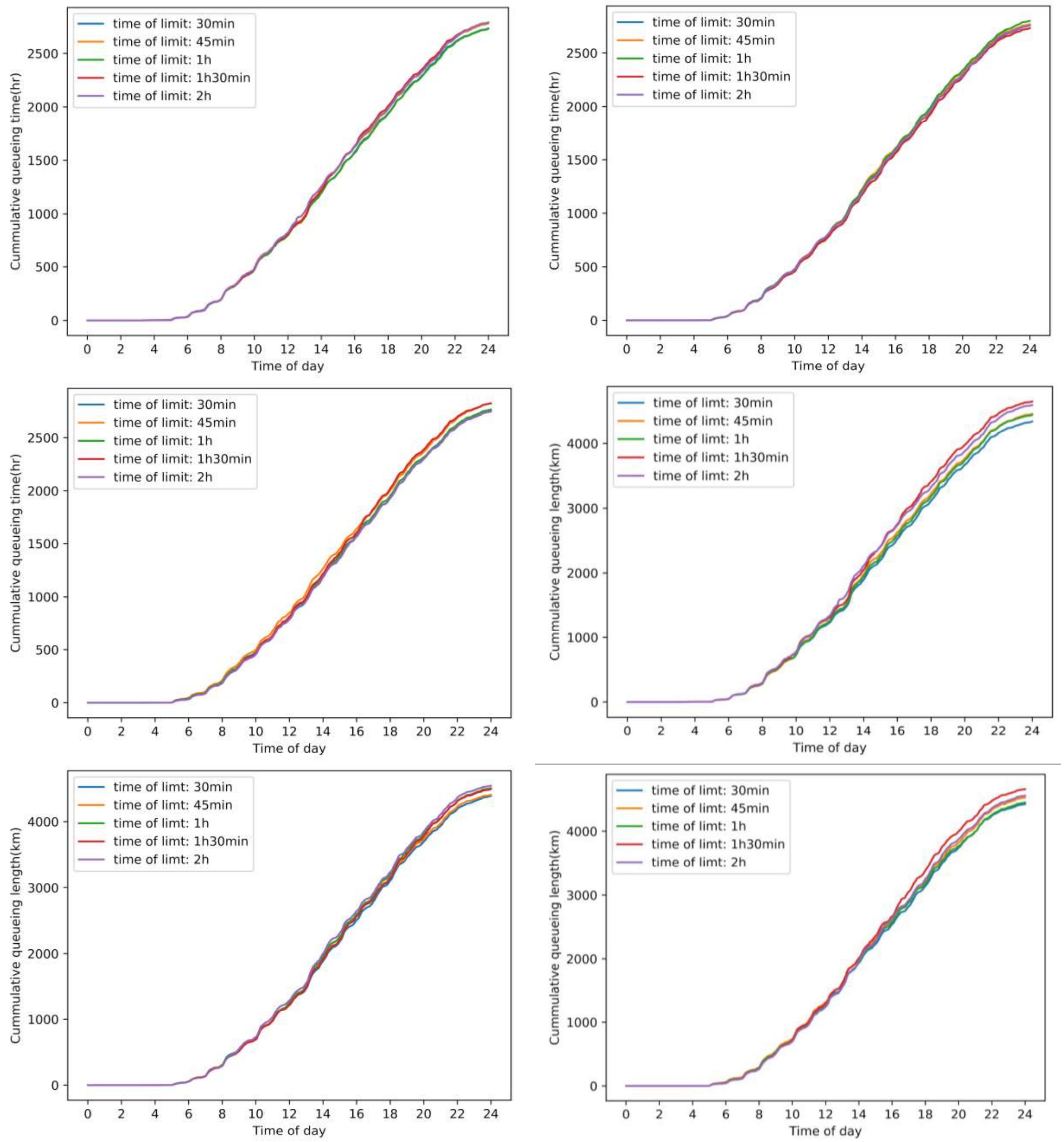

Figure C54. Mixed-use – Parking Time Limits – Queue Cumulative Length Results

11.4. Double Parking

11.4.1. Vehicle Kilometers Traveled Results

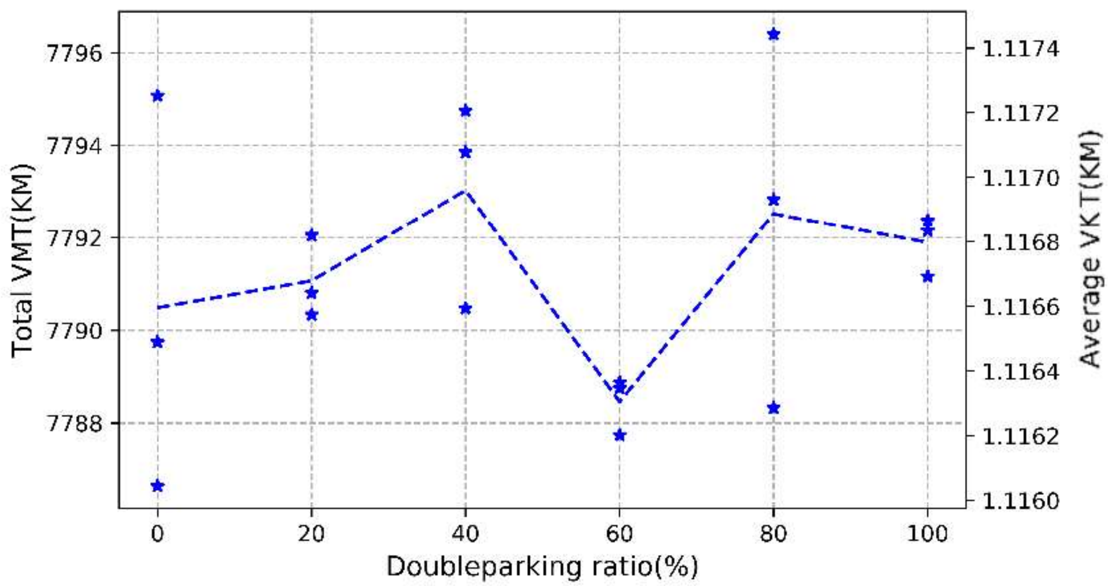

Figure C55. Mixed-use – Double Parking – VKT Results

11.4.2. Travel Time Results

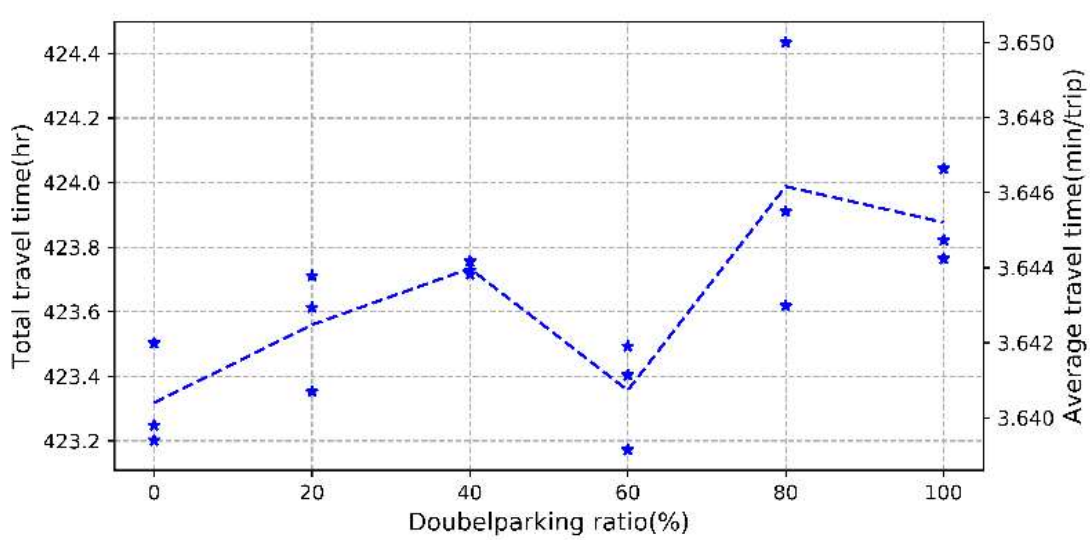

Figure C56. Mixed-use – Double Parking – Travel Times Results

11.4.3. Emissions Results

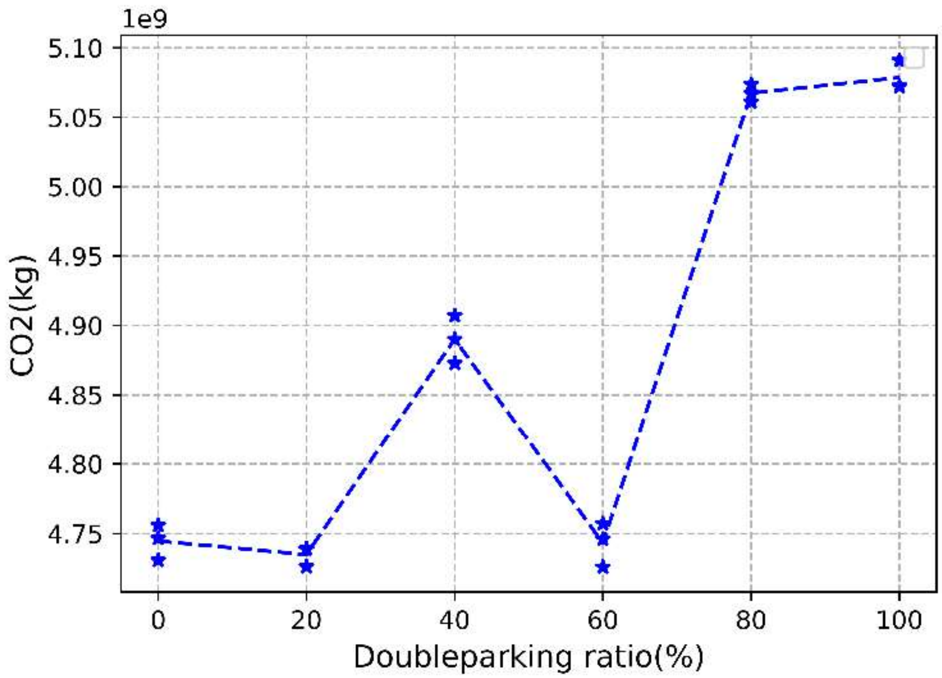

Figure C57. Mixed-use – Double Parking – Emissions Results

11.4.4. Queue Results

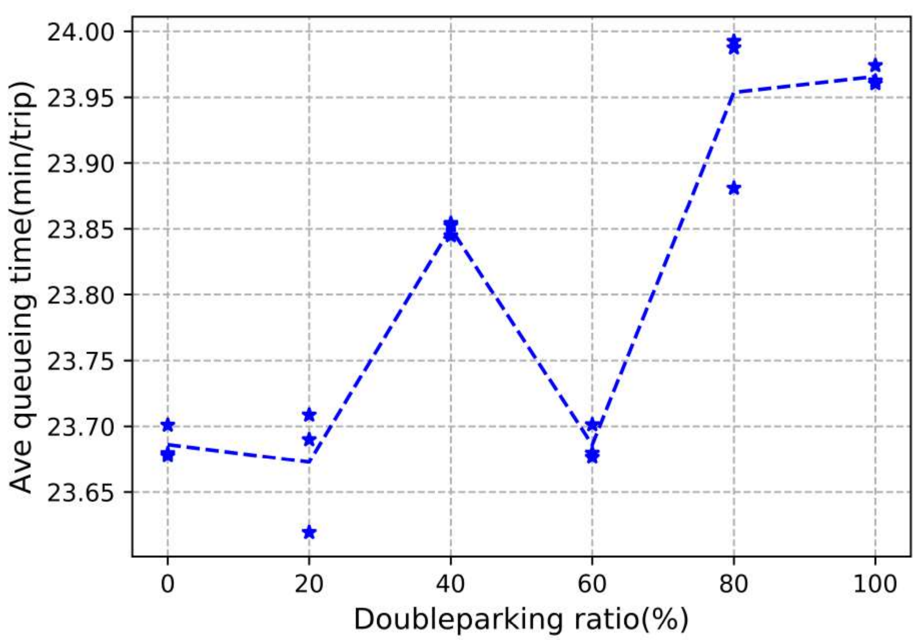

Figure C58. Mixed-use – Double Parking – Queue Times Results

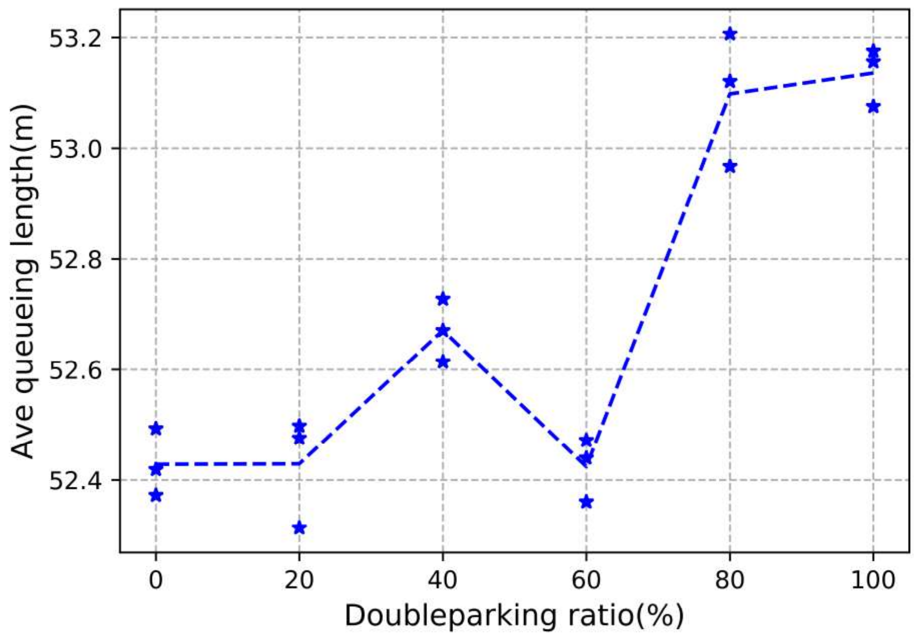

Figure C59. Mixed-use – Double Parking – Queue Length Results

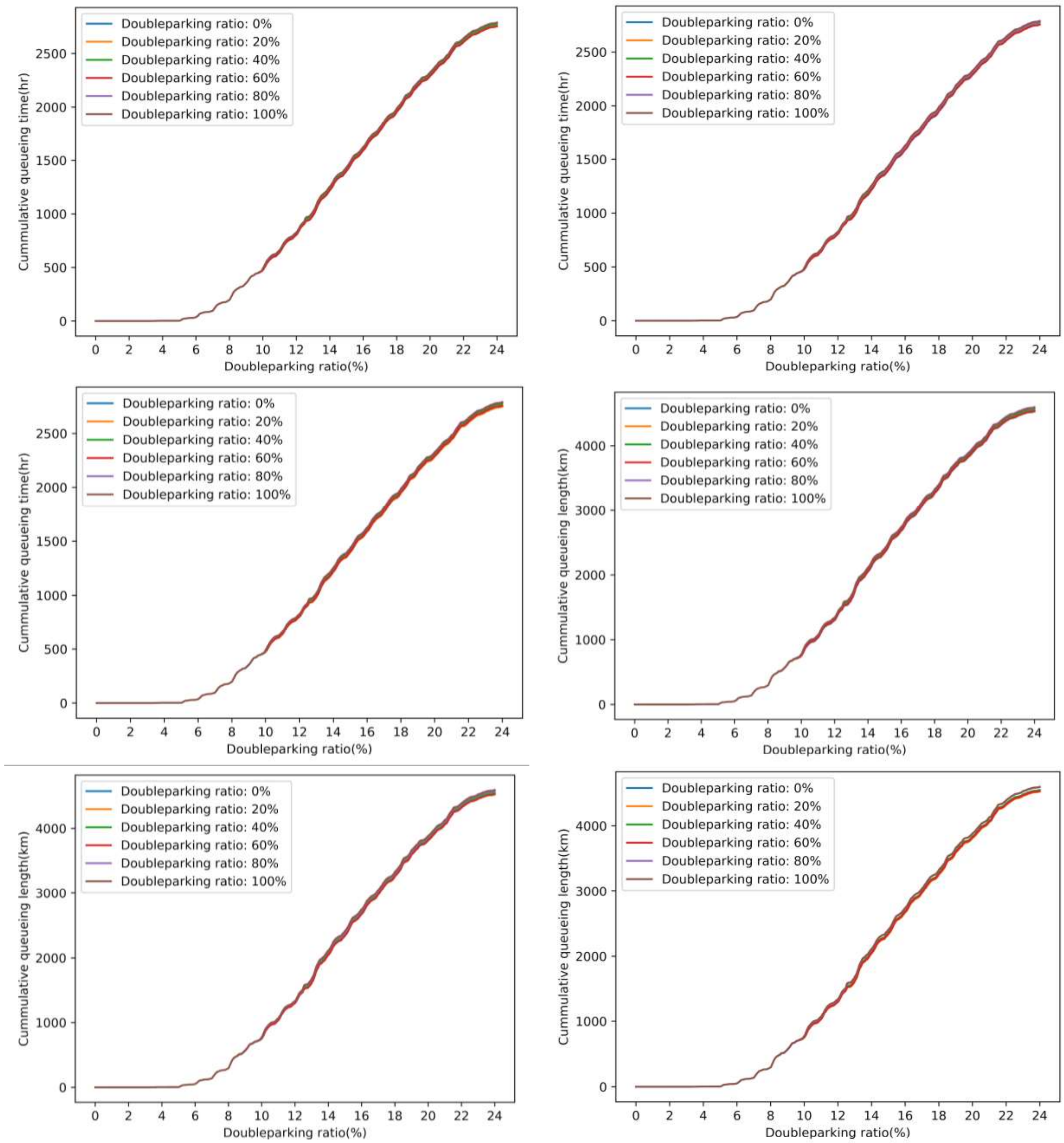

Figure C60. Mixed-use – Double Parking – Queue Cumulative Length Results

12. APPENDIX D. Commercial Area

12.1. Searching for On-street Parking and Off-street Availability

12.1.1. Vehicle Kilometers Traveled Results

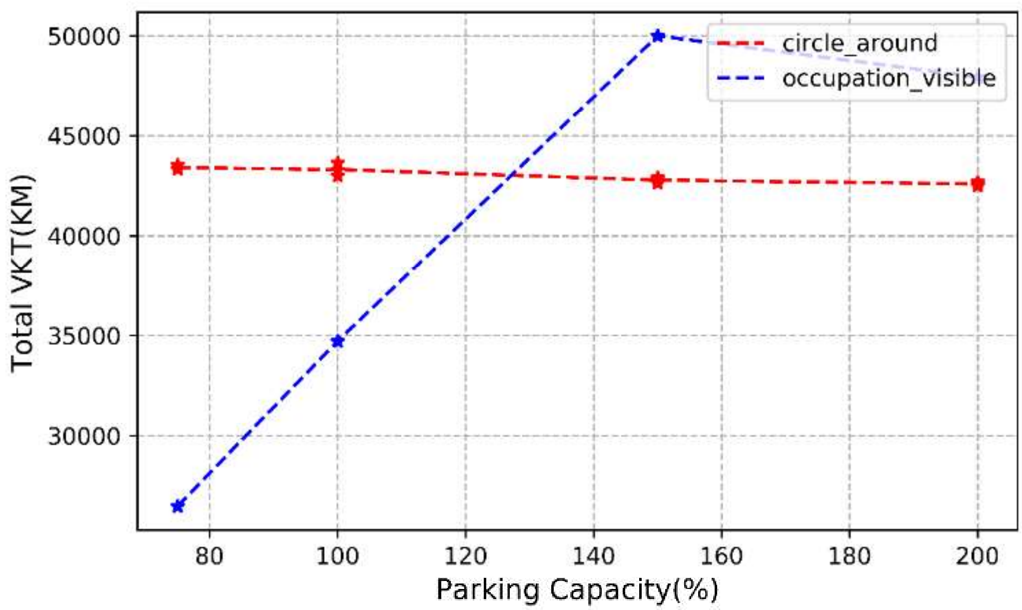

Figure D61. Commercial – Parking Search – VKT Results

12.1.2. Travel Time Results

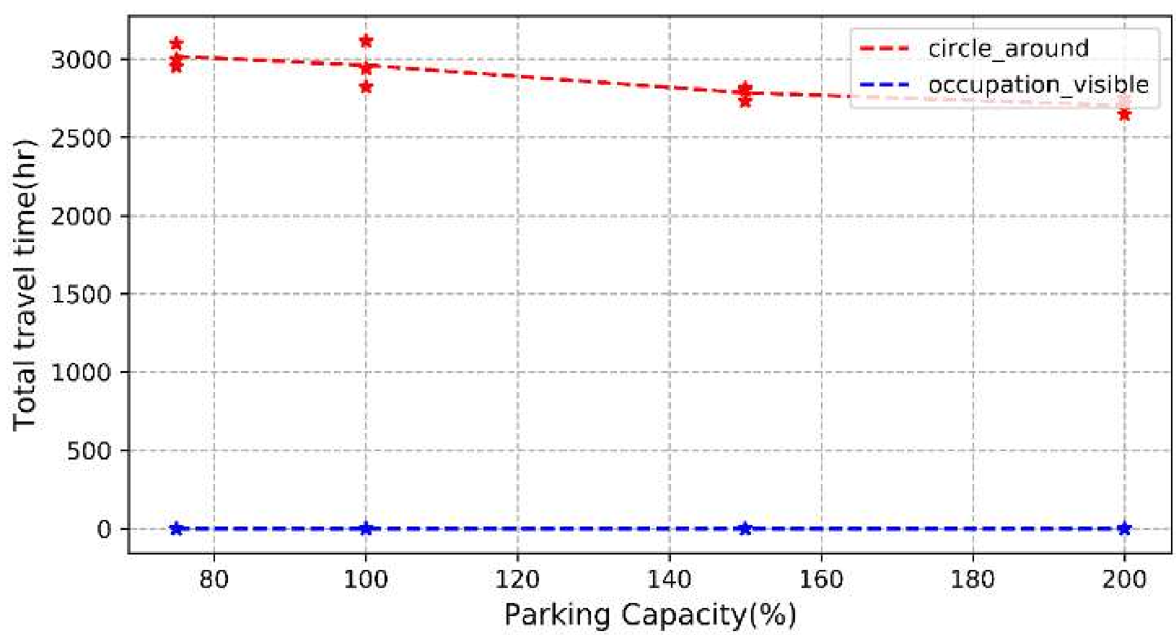

Figure D62. Commercial – Parking Search – Travel Times Results

12.1.3. Emissions Results

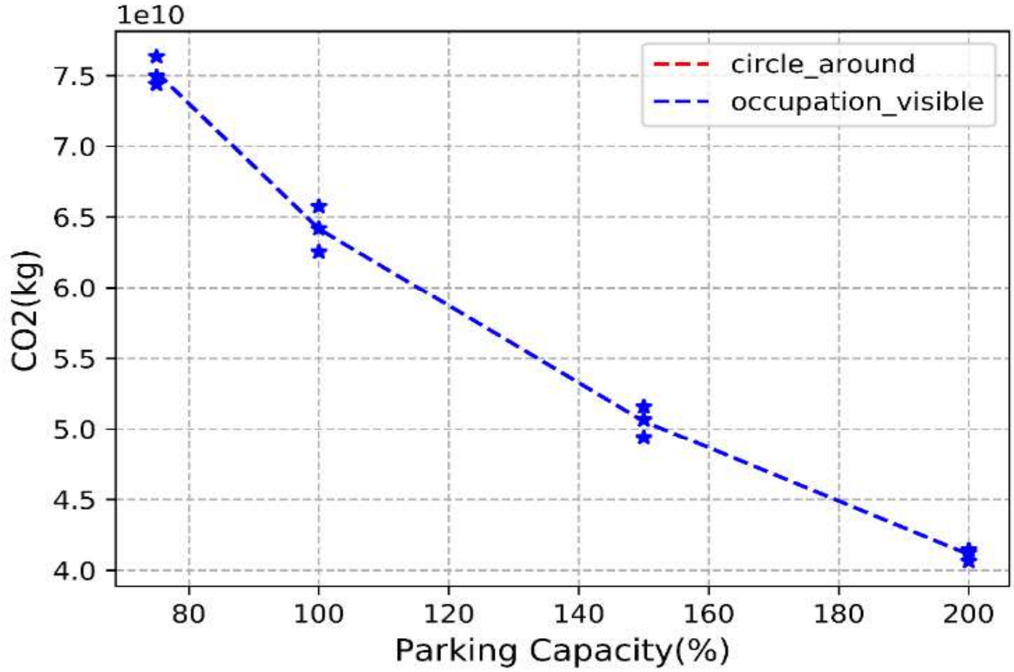

Figure D63. Commercial – Parking Search – Emissions Results

12.1.4. Queue Results

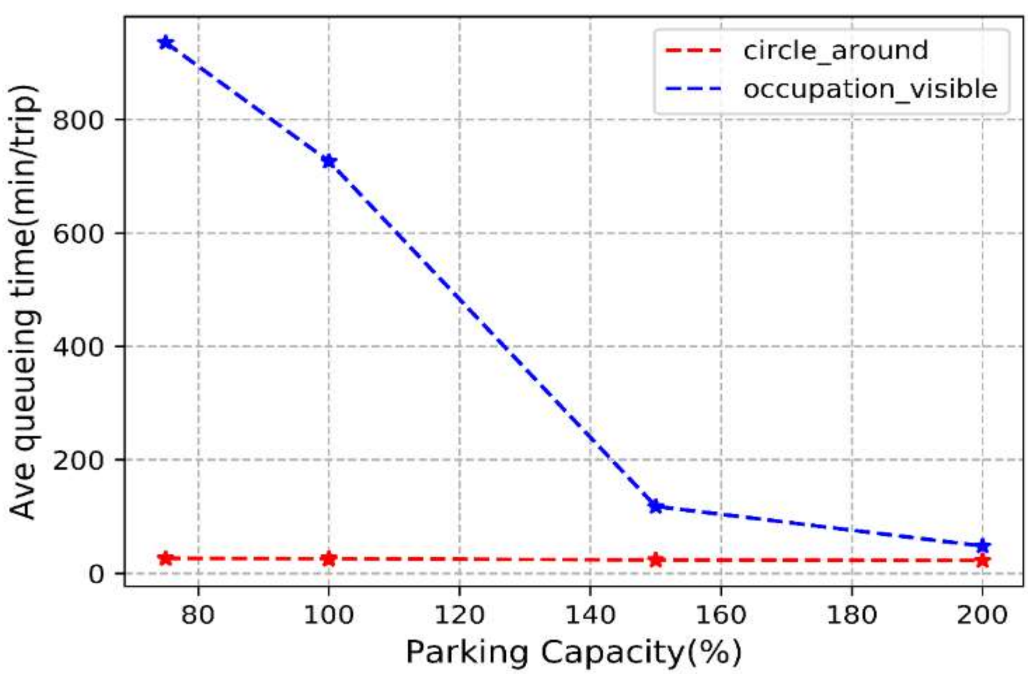

Figure D64. Commercial – Parking Search – Queue Times Results

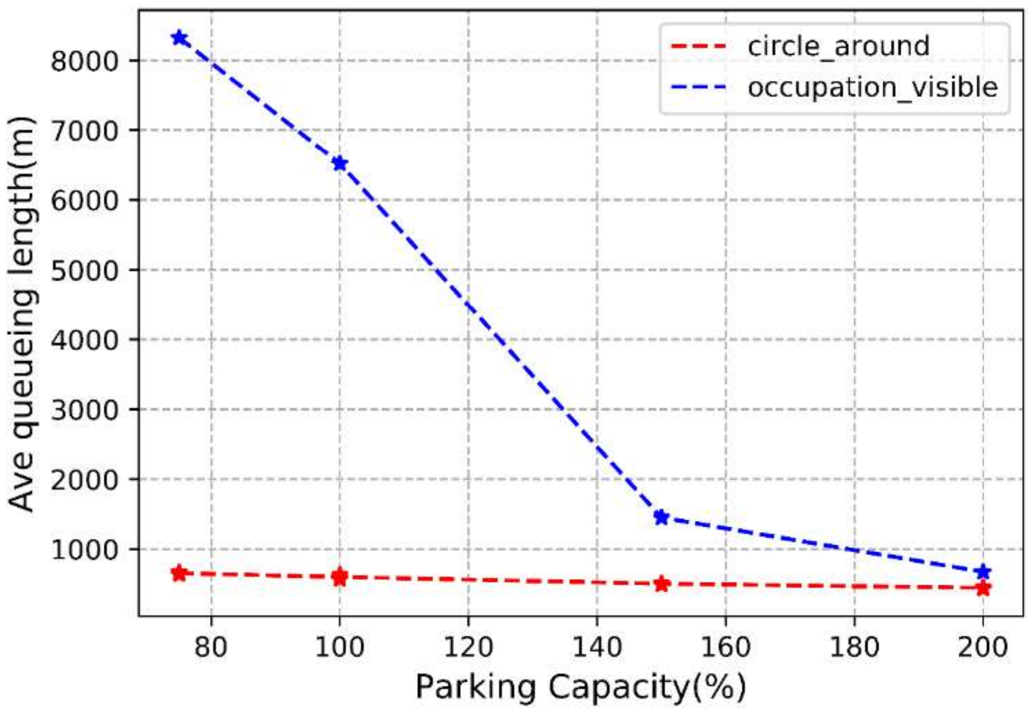

Figure D65. Commercial – Parking Search – Queue Length Results

12.2. Designated Loading and Unloading Areas

12.2.1. Vehicle Kilometers Traveled Results

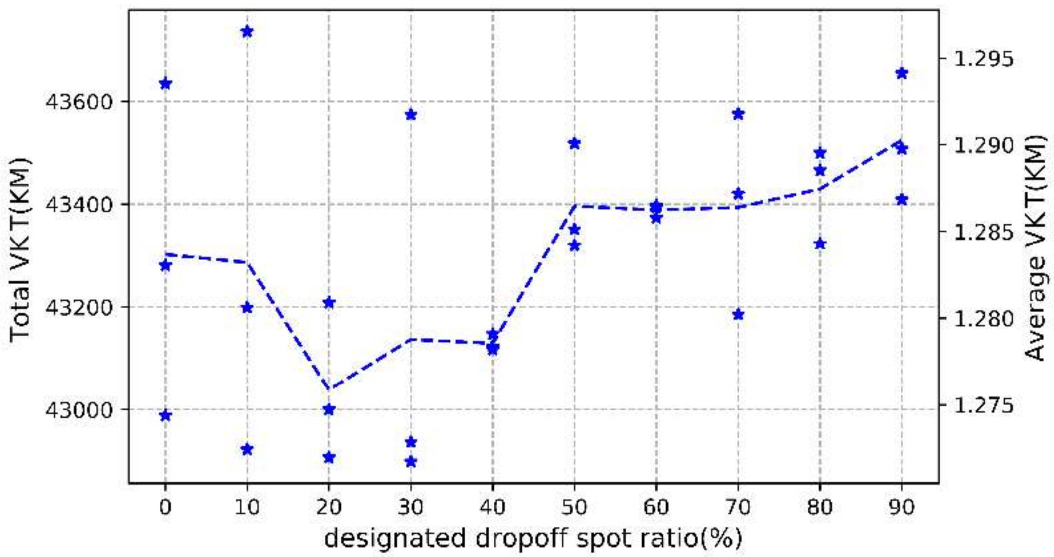

Figure D66. Commercial – Designated Parking – VKT Results

12.2.2. Travel Time Results

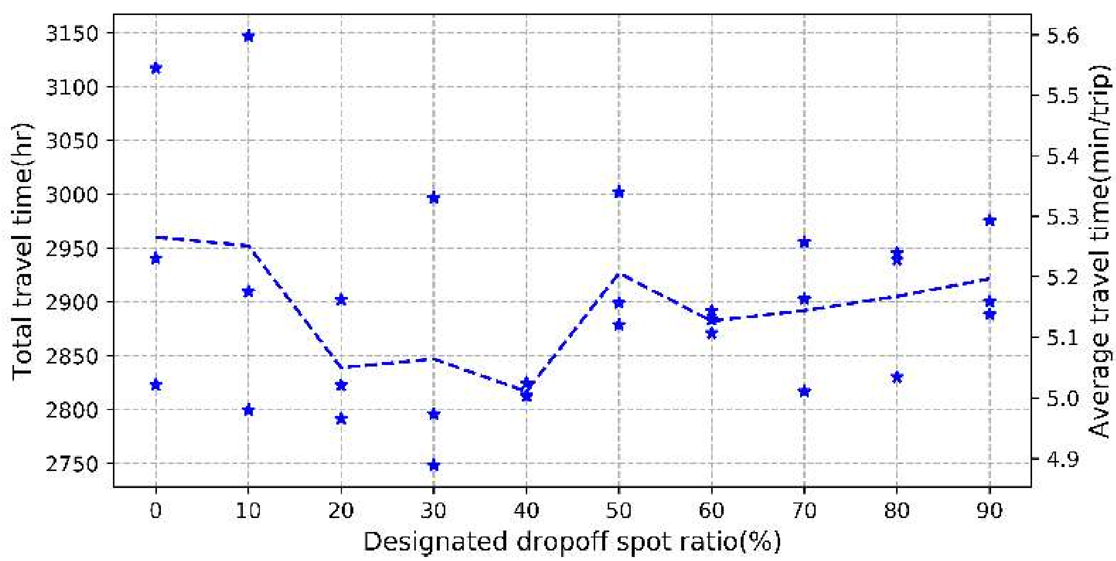

Figure D67. Commercial – Designated Parking – Travel Times Results

12.2.3. Emissions Results

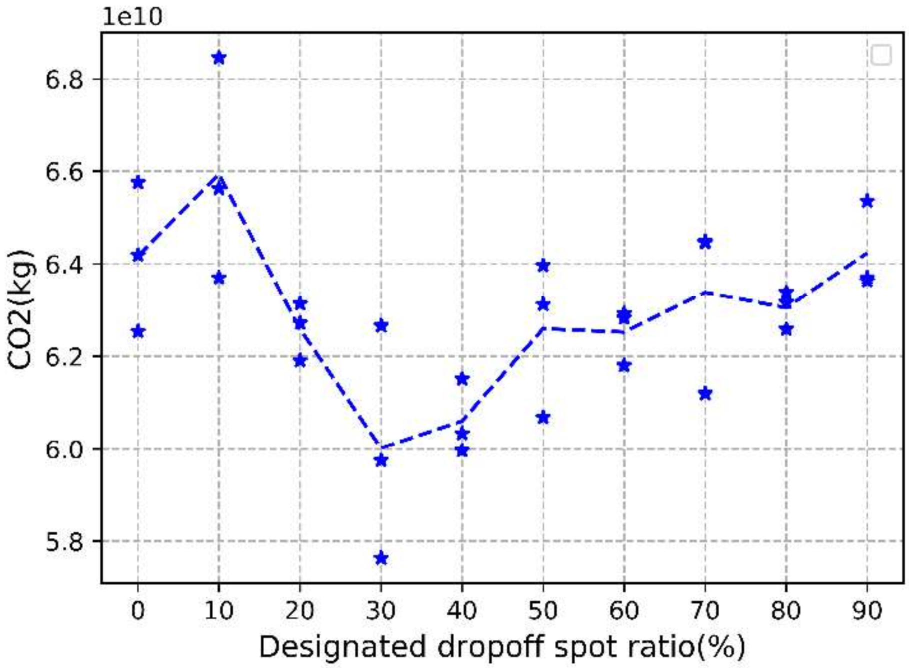

Figure D68. Commercial – Designated Parking – Emissions Results

12.2.4. Queue Results

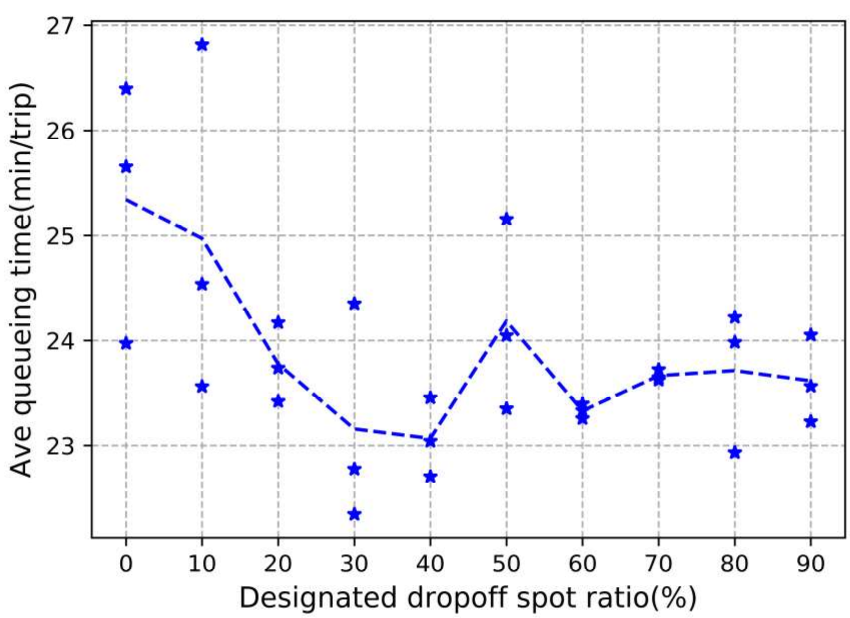

Figure D69. Commercial – Designated Parking – Queue Times Results

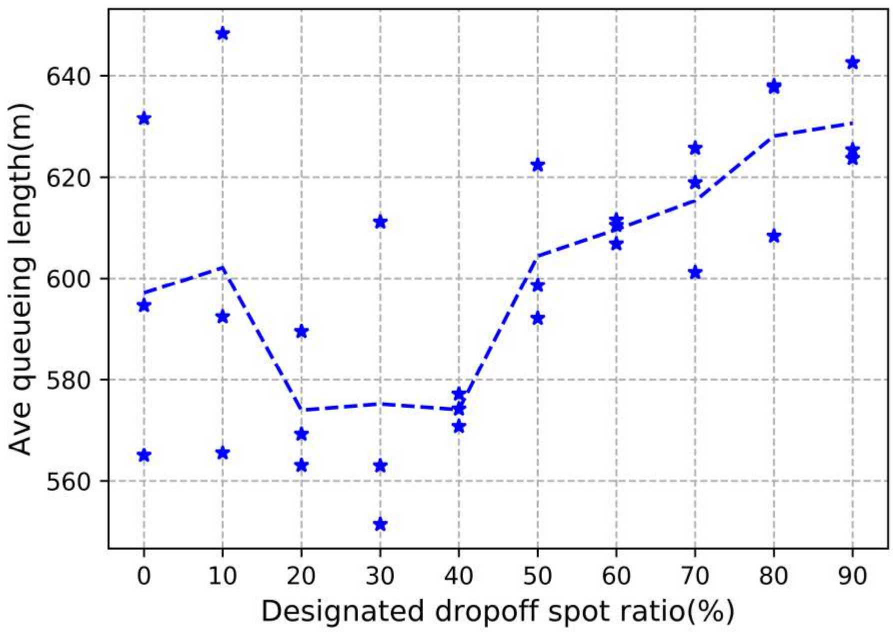

Figure D70. Commercial – Designated Parking – Queue Length Results

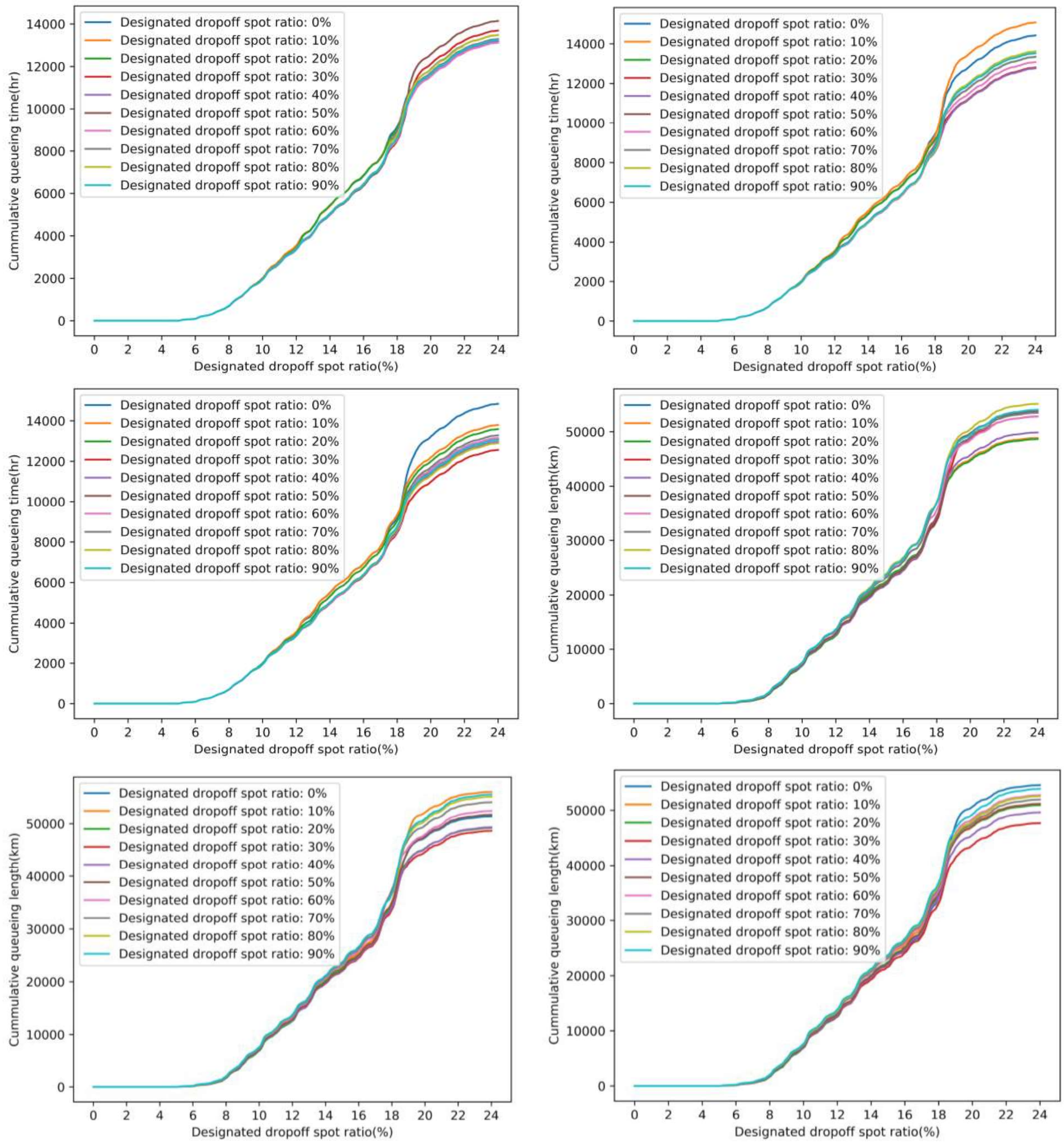

Figure D71. Commercial – Designated Parking – Queue Cumulative Length Results

12.3. Parking Time Limits

12.3.1. Vehicle Kilometers Traveled Results

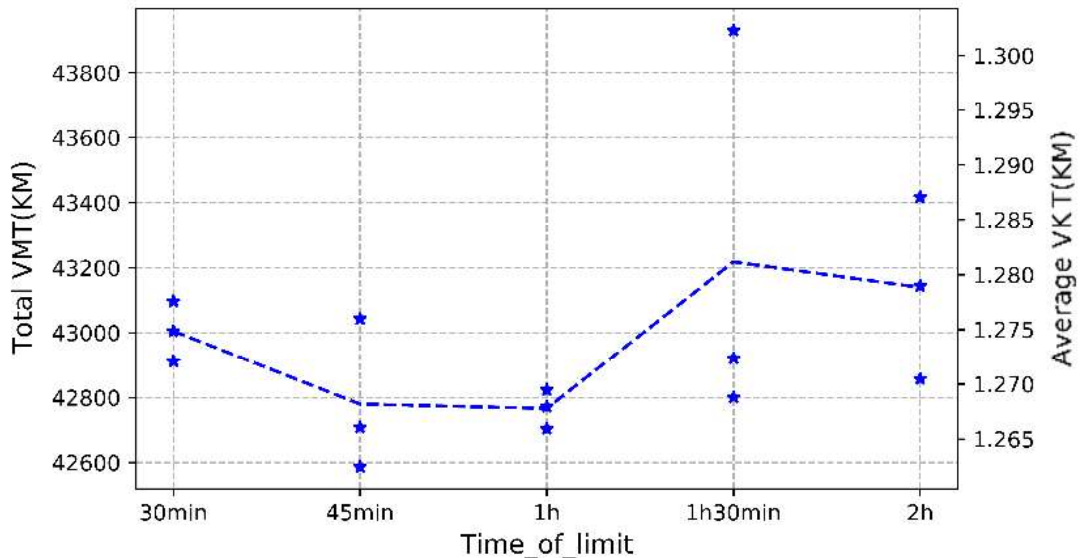

Figure D72. Commercial – Parking Time Limits – VKT Results

12.3.2. Travel Time Results

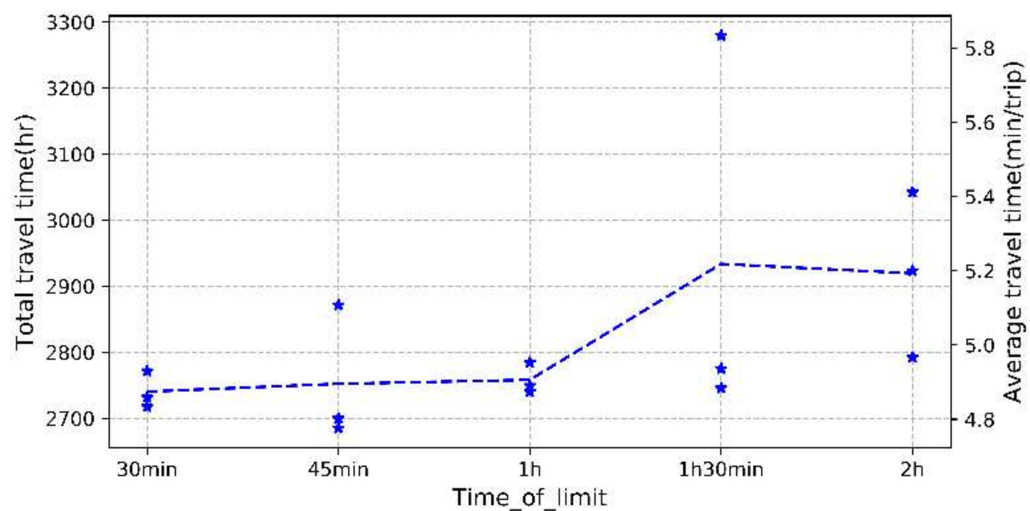

Figure D73. Commercial – Parking Time Limits – Travel Times Results

12.3.3. Emissions Results

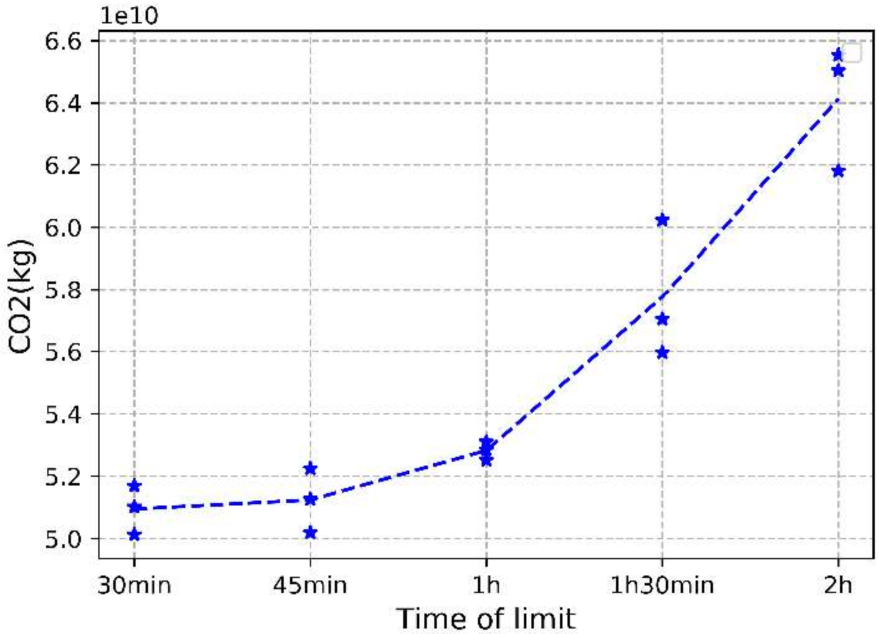

Figure D74. Commercial – Parking Time Limits – Emissions Results

12.3.4. Queue Results

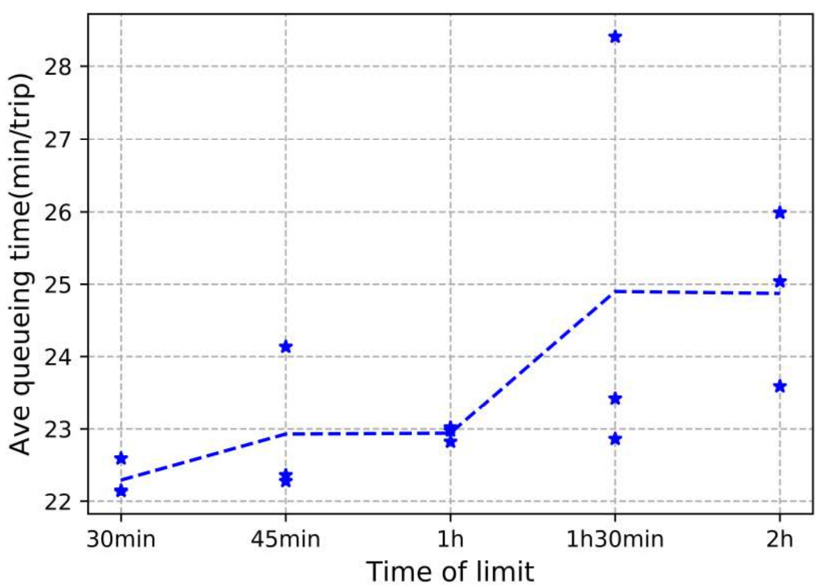

Figure D75. Commercial – Parking Time Limits – Queue Times Results

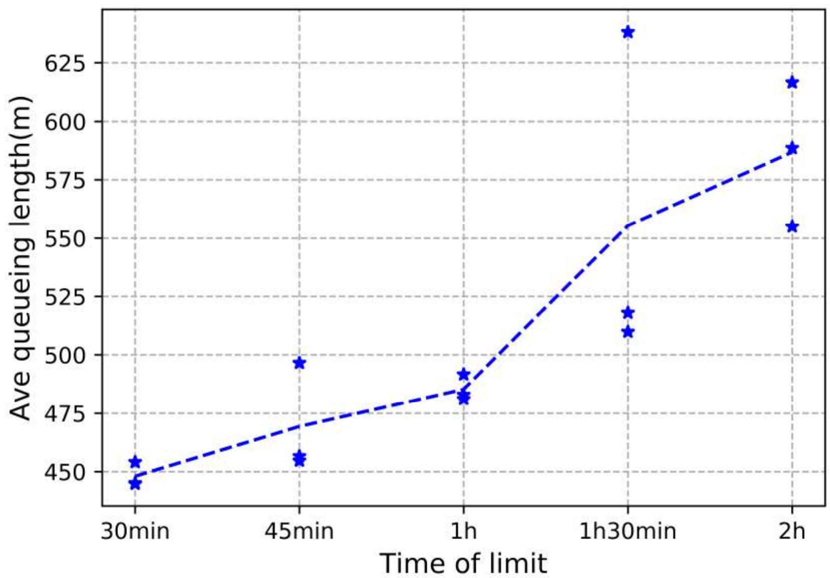

Figure D76. Commercial – Parking Time Limits – Queue Length Results

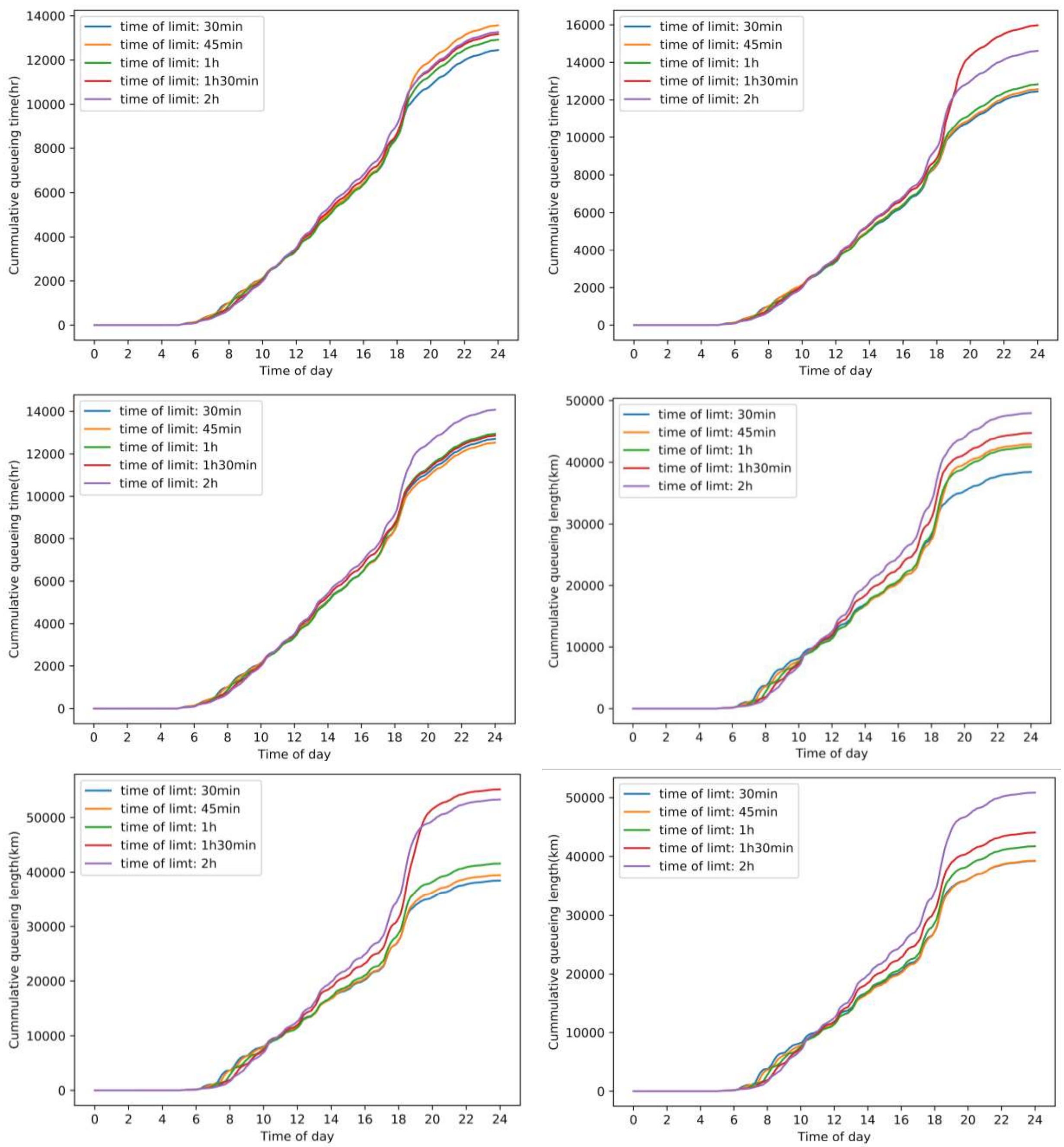

Figure D77. Commercial – Parking Time Limits – Queue Cumulative Length Results

12.4. Double Parking

12.4.1. Vehicle Kilometers Traveled Results

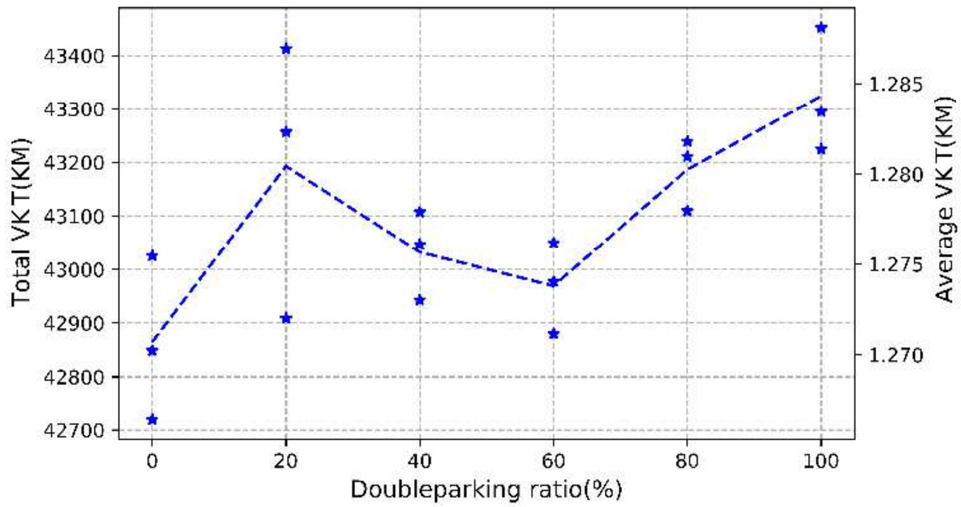

Figure D78. Commercial – Double Parking – VKT Results

12.4.2. Travel Time Results

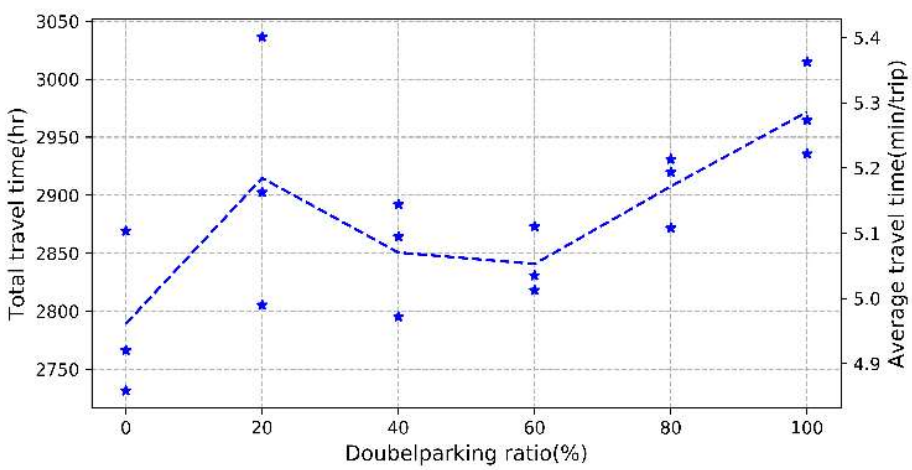

Figure D79. Commercial – Double Parking – Travel Times Results

12.4.3. Emissions Results

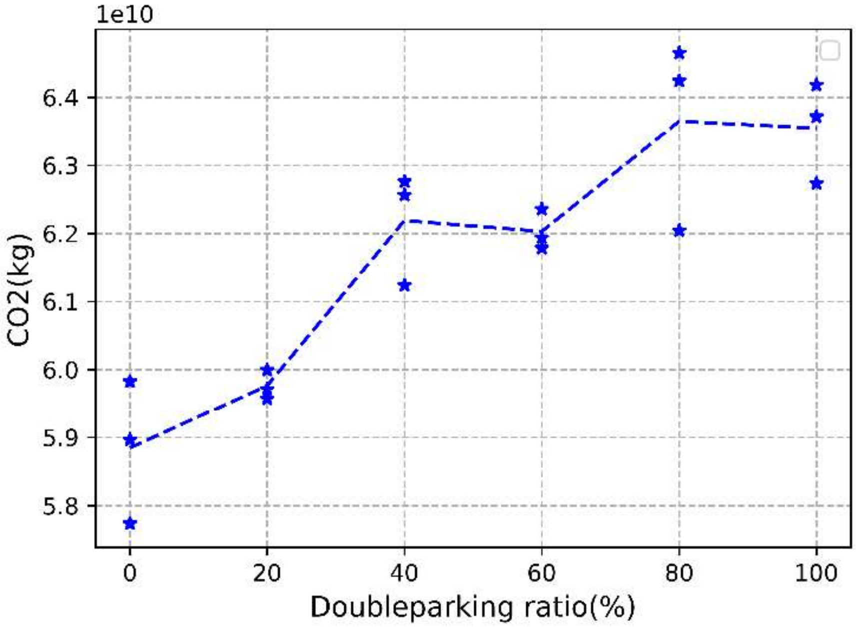

Figure D80. Commercial – Double Parking – Emissions Results

12.4.4. Queue Results

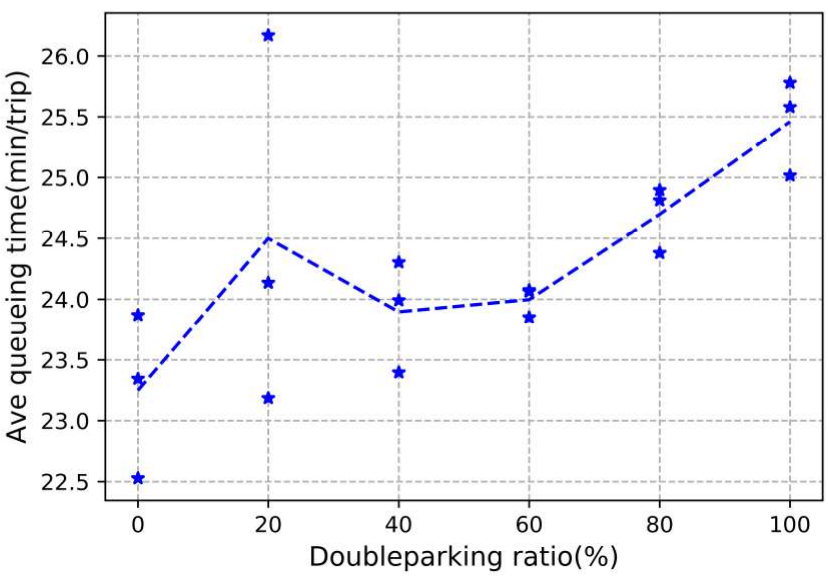

Figure D81. Commercial – Double Parking – Queue Times Results

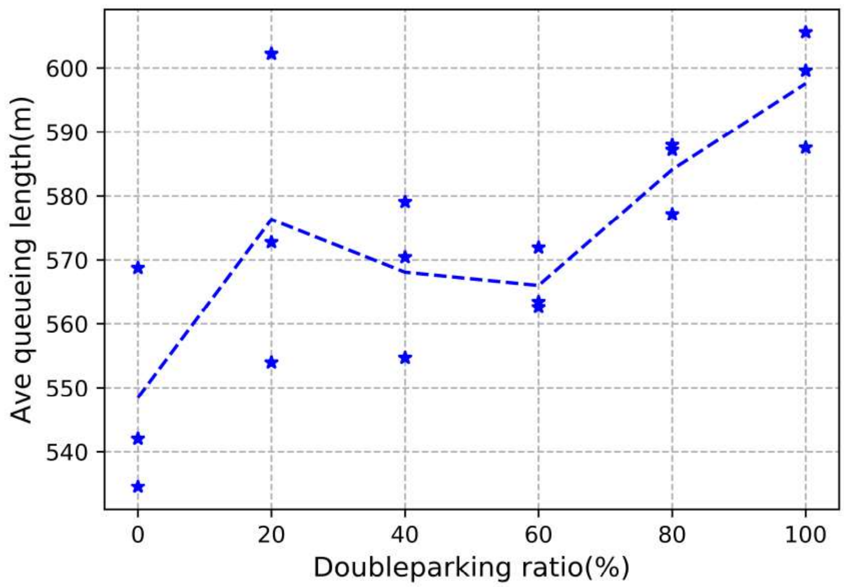

Figure D82. Commercial – Double Parking – Queue Length Results

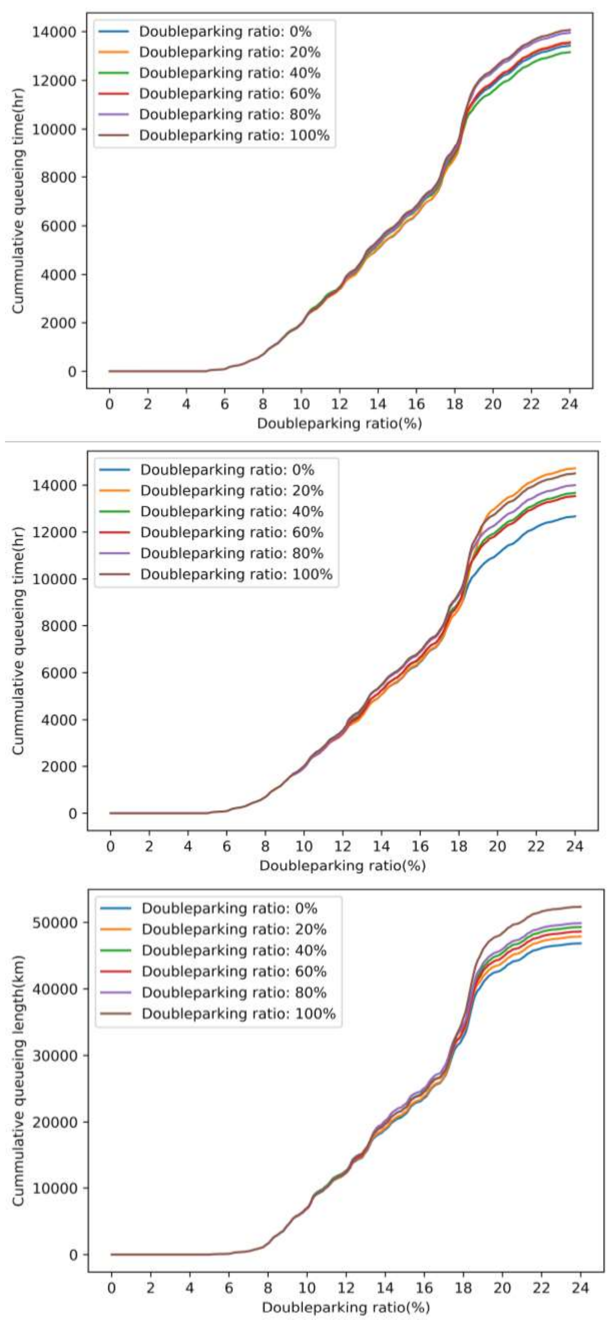

Figure D83. Commercial – Double Parking – Queue Cumulative Length Results

12.5. Disaggregate Results of Parking Time Limit Scenarios

12.5.1. Morning Peak Vehicle Kilometers Traveled Results for Parking Time Limit Scenario

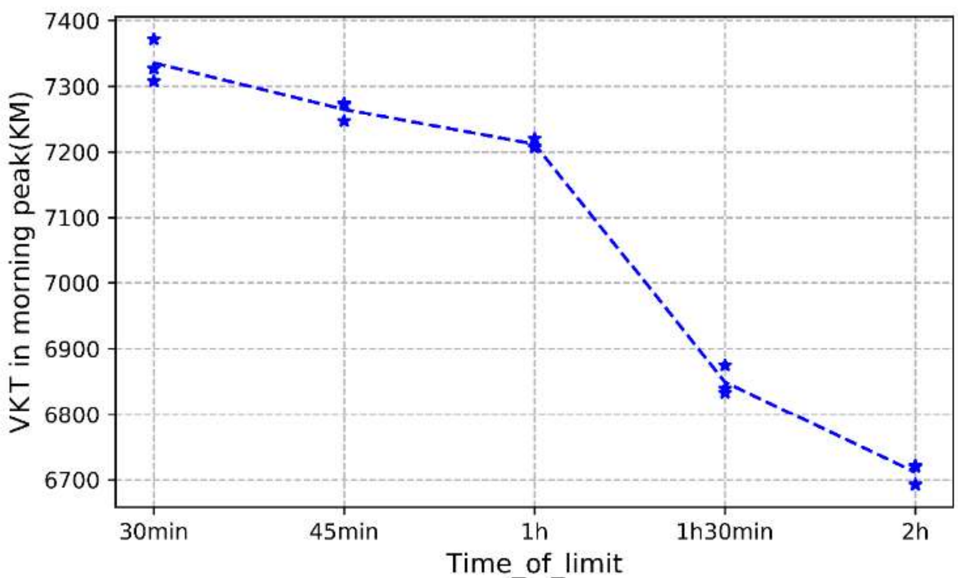

Figure D84. Commercial – Parking Time Limits – VKT – Morning Peak Results

12.5.2. Afternoon Peak Vehicle Kilometers Traveled Results for parking time limit scenario

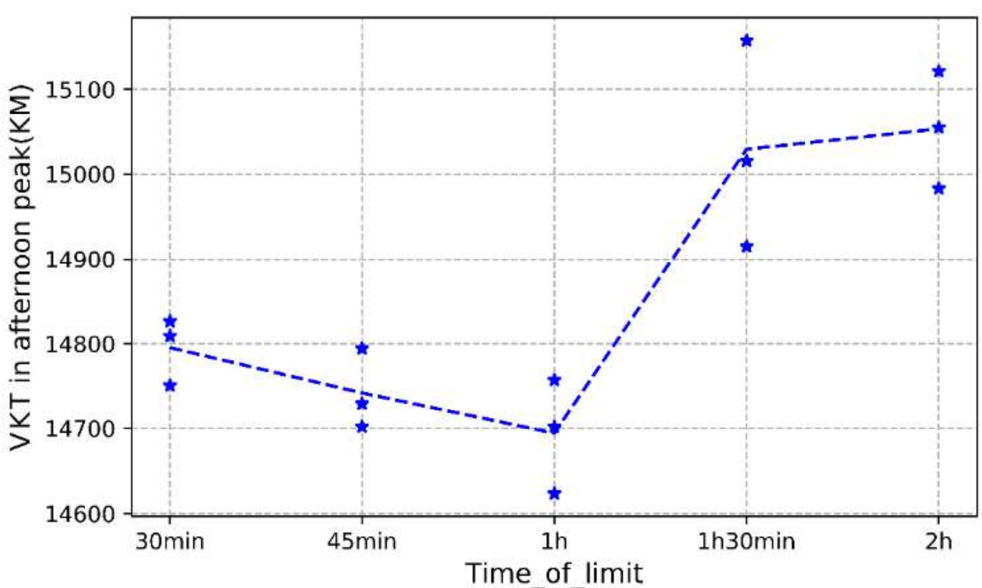

Figure D85. Commercial – Parking Time Limits – VKT– Afternoon Peak Results

12.5.3. Morning Peak Queue Results for Time Limits

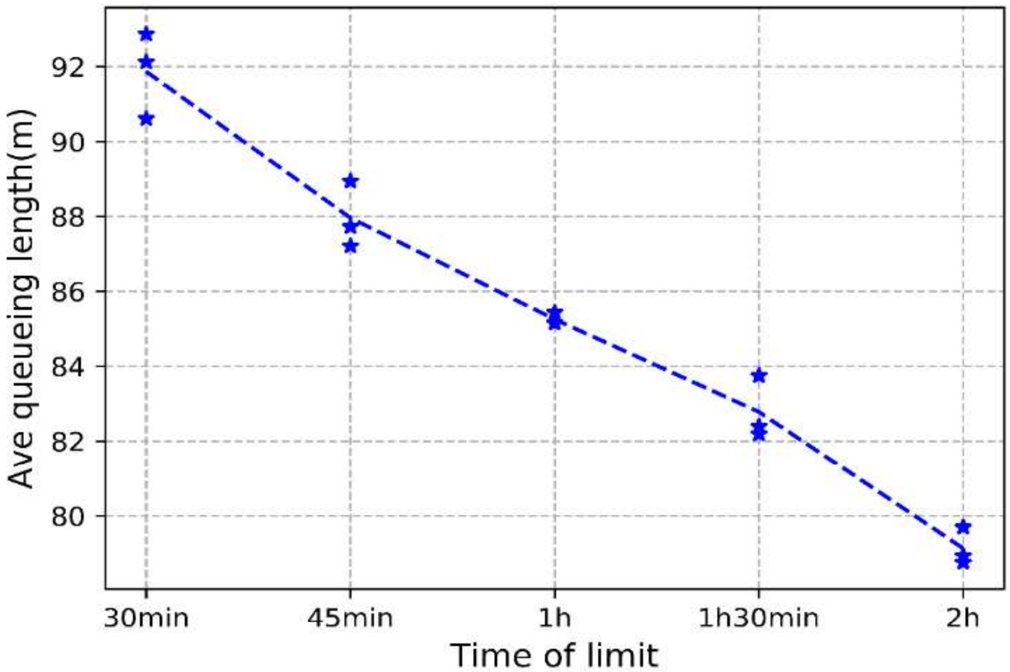

Figure D86. Commercial – Parking Time Limits – Queue Lengths – Morning Peak Results

12.5.4. Afternoon Peak Queue Results for Time Limits

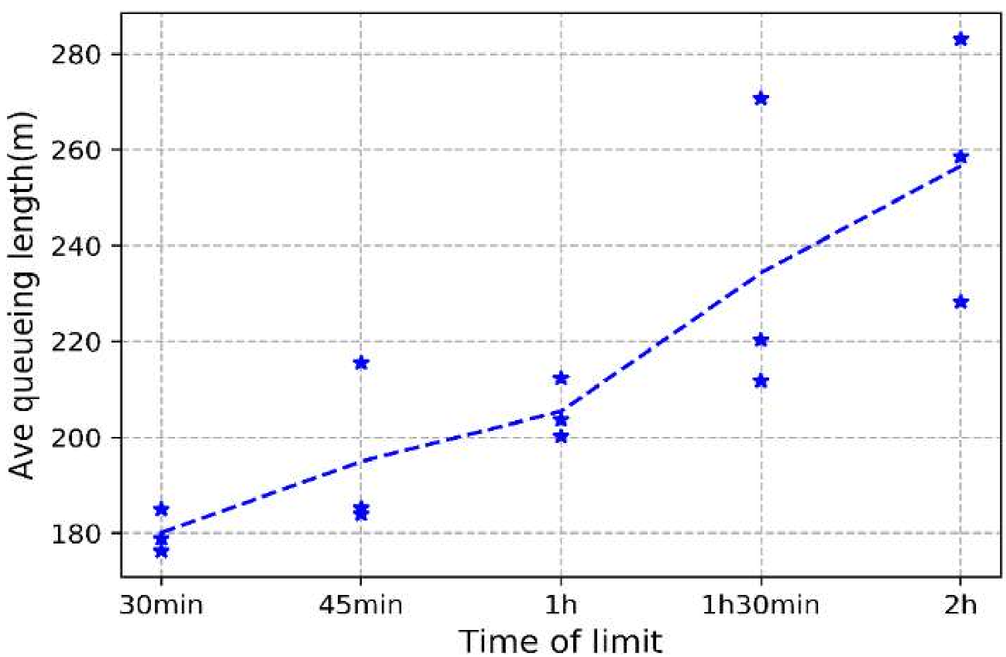

Figure D87. Commercial – Parking Time Limits – Queue Lengths – Afternoon Peak Results

12.6. Disaggregate Results of Designated Loading/Unloading Areas

12.6.1. Vehicle Kilometers Traveled Results for Passenger Vehicles

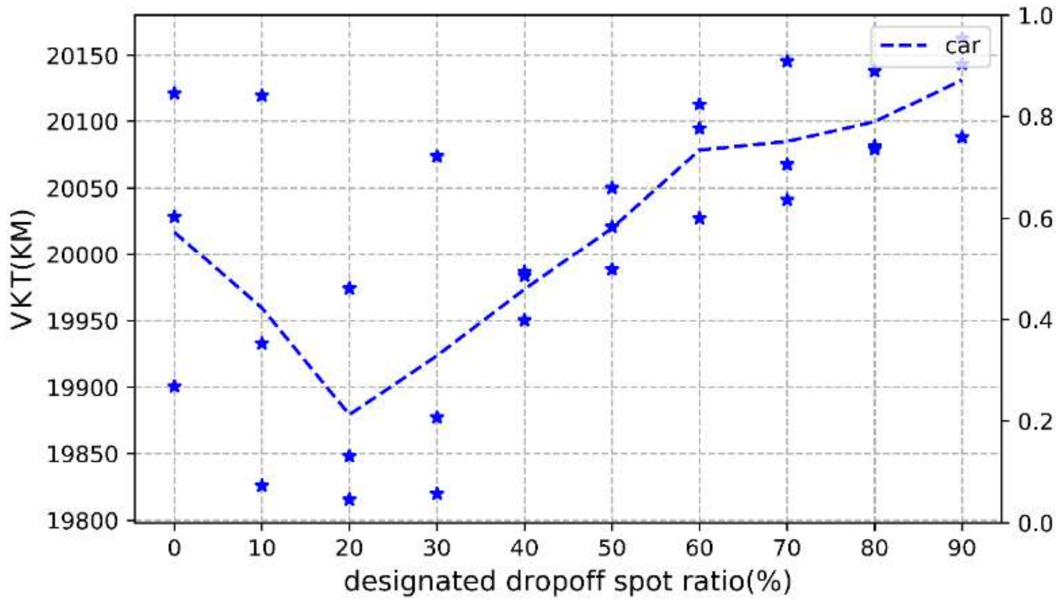

Figure D88. Commercial – Passenger Vehicles – VKT Results

12.6.2. Morning Peak Vehicle Kilometers Traveled Results for Passenger Vehicles

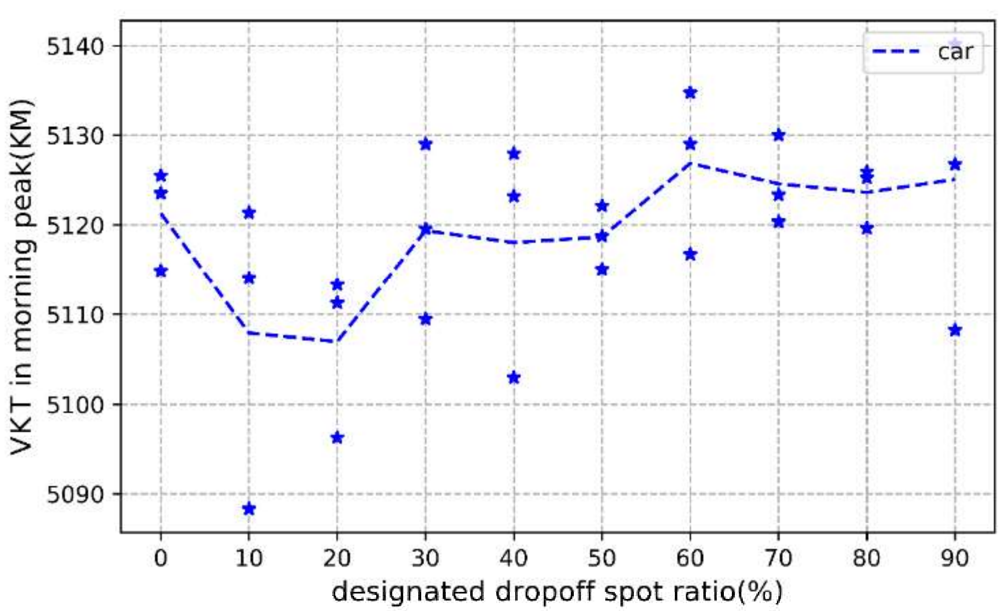

Figure D89. Commercial – Passenger Vehicles – VKT – Morning Peak Results

12.6.3. Afternoon Peak Vehicle Kilometers Traveled Results for Passenger Vehicles

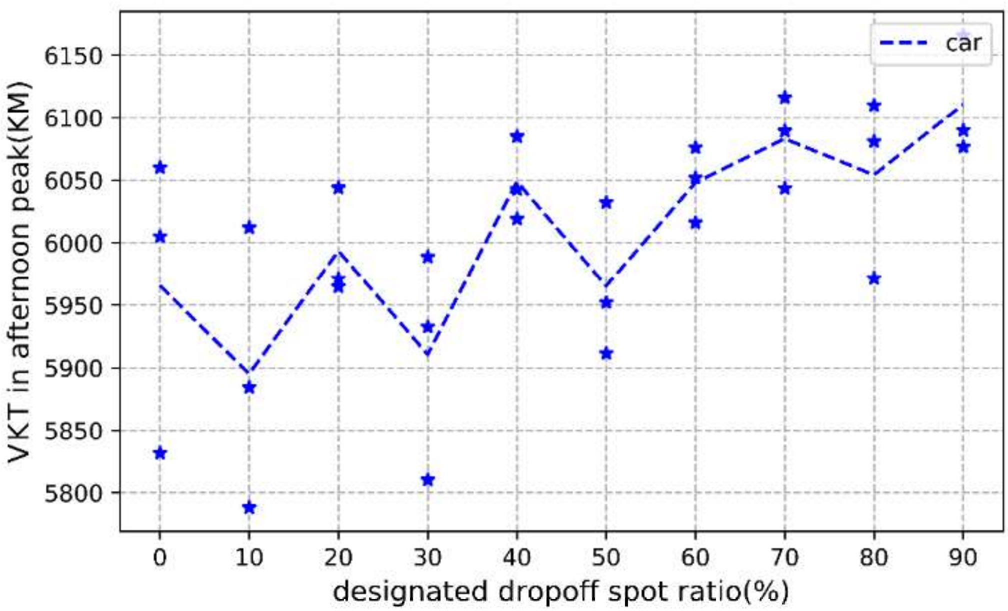

Figure D90. Commercial – Passenger Vehicles – VKT – Afternoon Peak Results

12.6.4. Vehicle Kilometers Traveled Results for Taxi

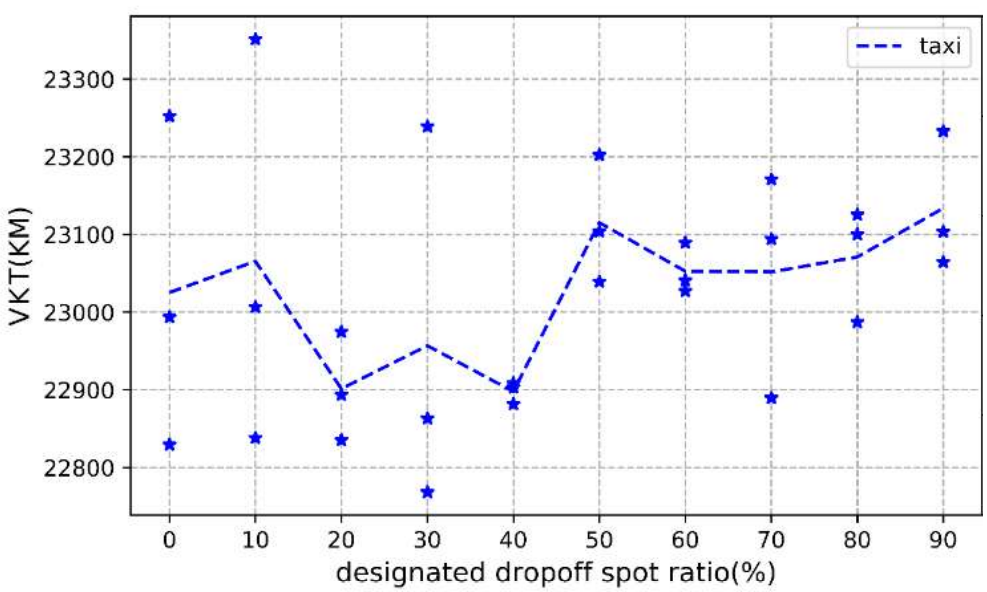

Figure D91. Commercial – Taxi – VKT Results

12.6.5. Morning Peak Vehicle Kilometers Traveled Results for Taxi

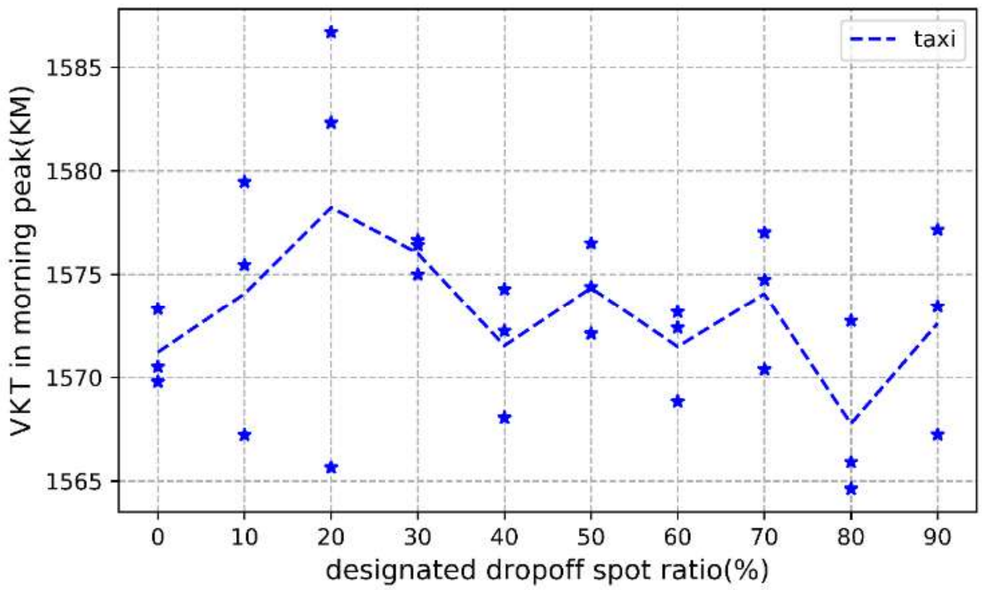

Figure D92. Commercial – Taxi – VKT – Morning Peak Results

12.6.6. Afternoon Peak Vehicle Kilometers Traveled Results for Taxi

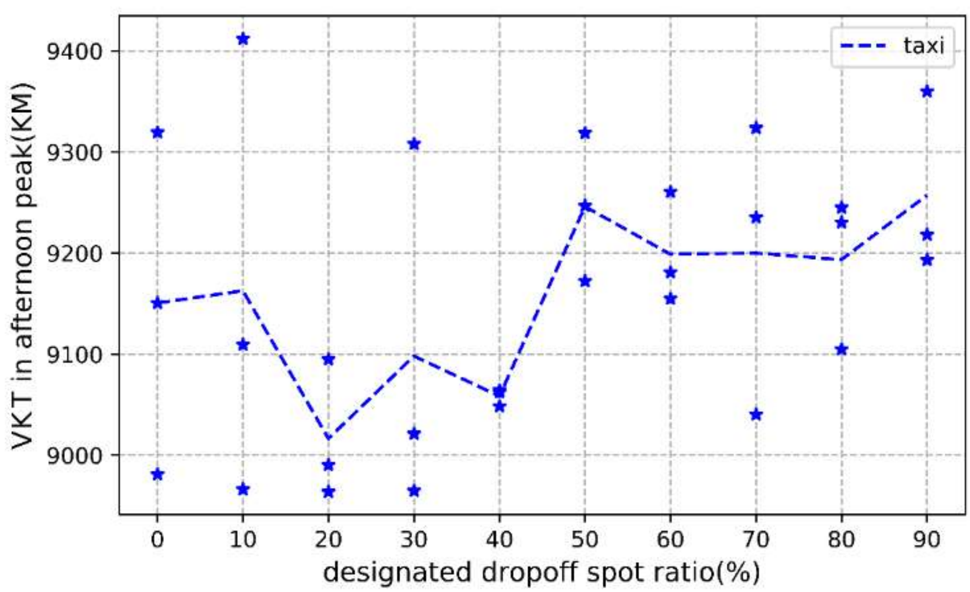

Figure D93. Commercial –Taxi – VKT – Afternoon Peak Results

12.6.7. Vehicle Kilometers Traveled Results for Commercial Vehicles

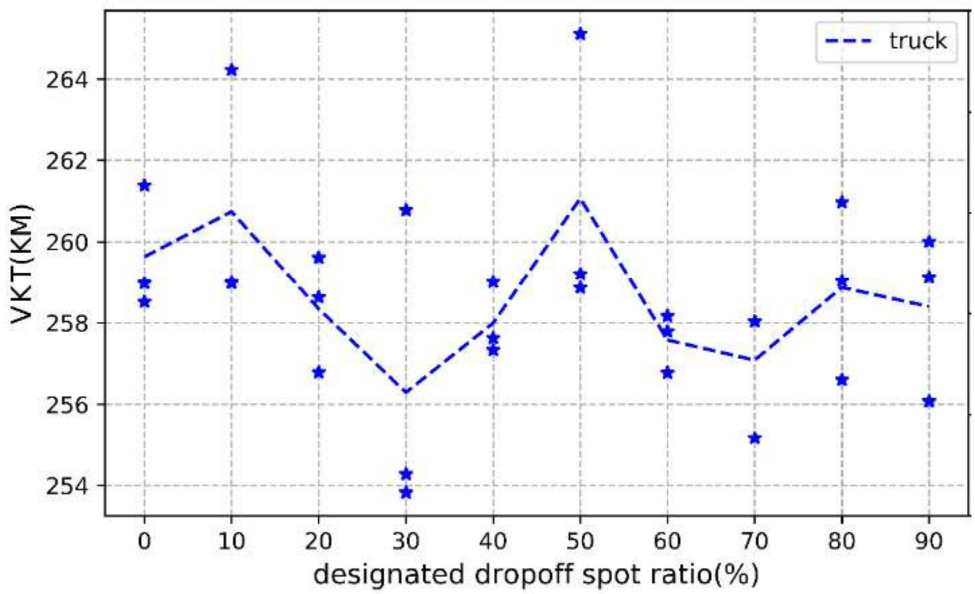

Figure D94. Commercial – Commercial Vehicles – VKT Results

12.6.8. Morning Peak Vehicle Kilometers Traveled Results for Commercial Vehicles

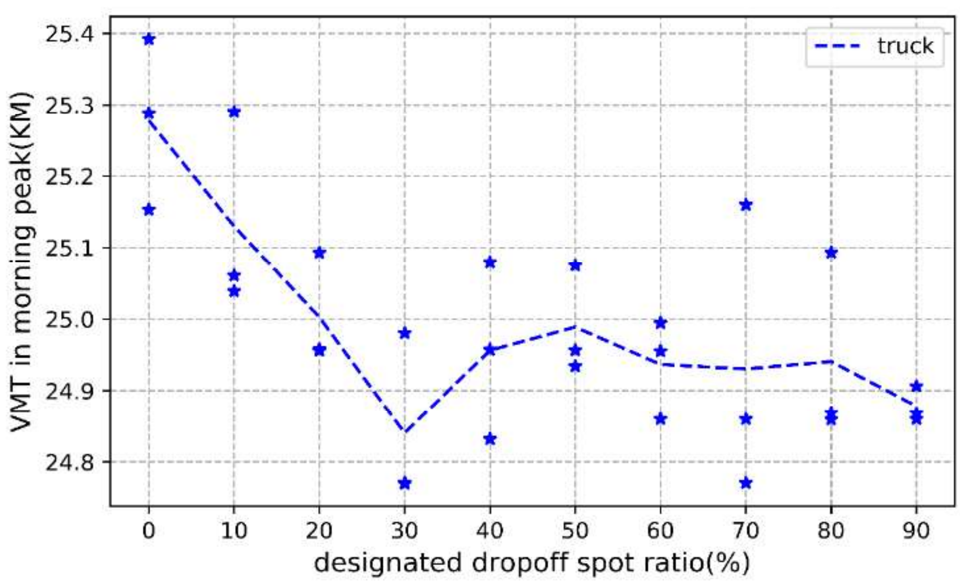

Figure D95. Commercial – Commercial Vehicles – VKT – Morning Peak Results

12.6.9. Afternoon Peak Vehicle Kilometers Traveled Results for Commercial Vehicles

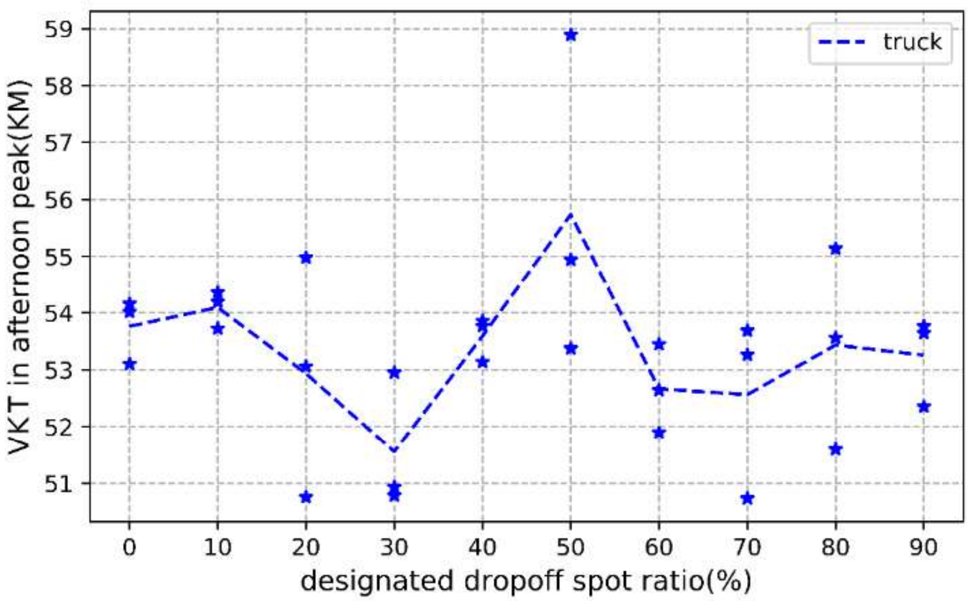

Figure D96. Commercial – Commercial Vehicles – VKT – Afternoon Peak Results