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16. Abstract
The potential for automated vehicles (AVs) to reduce parking in city centers has generated much excitement among urban planners. AVs could drop-off (DO) and pick-up (PU) passengers in areas where parking costs are high: personal AVs could return home or park in less expensive locations, and shared AVs could serve other passengers. Reduced on-street and off-street parking present numerous opportunities for redevelopment that could improve the livability of cities, for example, more street and sidewalk space for pedestrian and bicycle travel. However, reduced demand for parking would be accompanied by increased demand for curbside DO/PU space with related movements to enter and exit the flow of traffic. This change could be particularly challenging for traffic flows in downtown urban areas during peak hours, where high volumes of DOs and PUs are likely to occur. Only limited research examines the travel effects of a shift from parking to DO/PU travel and the impact of changes in parking supply. This study uses a microscopic road traffic model with local travel activity data to simulate personal AV parking scenarios in San Francisco's downtown central business district. These scenarios vary (1) the demand for DO and PU travel versus parking, (2) the supply of on-street and off-street parking, and (3) the total demand for parking and DO/PU travel due to an increase in the cost of travel to the central business district.

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A Research Report from the National Center for Sustainable Transportation

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National Center for Sustainable Transportation

UC DAVIS INSTITUTE OF TRANSPORTATION STUDIES

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TABLE OF CONTENTS

Glossary....................iii
EXECUTIVE SUMMARY....................iv
Introduction....................1
Literature Review....................1
Methodology....................2
  Modeling....................2
  Network and Traffic Analysis Zones....................3
  Parking Supply Data....................4
  Parking Revenue....................5
  Emissions Impact Modeling....................5
Scenarios....................5
Results....................7
  Traffic Flow Results....................7
  VMT and Emission Results....................18
  Parking Revenue....................25
Conclusions....................27
References....................29
Data Management....................30

List of Figures

Figure ES-1. Scenario 1: Average (Avg.) daily VMT, empty VMT, and CO_2 emissions. v

Figure 1. (a) Study area: Central Business District for the City of Francisco. (b) Traffic Analysis Zones for MTC-ABM Model. 4

Figure 2. Average CBD speed (m/s) by the time of day, as the share of drop-off/pick-up demand substitutes for parking demand from 0% to 100% in 10% increments (Scenario Set 1). 8

Figure 3. Average daily roadway link-level occupancy results for scenario set 1 (0%, 50%, and 100% shift from parking traffic to drop-off/pick-up traffic). 9

Figure 4. Percentage change in average CBD speed at different times of the day if different percentages of on-street parking spaces (20–100%) are reallocated to drop-off/pick-up spaces. 10

Figure 5. Average daily roadway link-level occupancy results for scenario set 2 (20%, 60%, and 100% of on-street parking spaces converted to drop-off/pick-up spaces). 11

Figure 6. Average CBD speed (m/s) by the hour of the day with the distribution of off-street parking supply concentrated in randomly located, fewer off-street facilities (Scenario Set 3). 12

Figure 7. Average daily roadway link-level occupancy results for scenario set 3 (conversion of 0%, 40%, and 80% of on-street parking spaces to drop-off/pick-up spaces). 13

Figure 8. Percentage change in average hourly CBD vehicle speeds if traffic is reduced by 30% in scenarios 1, 2, and 3. 14

Figure 9. Average daily link-level road occupancy when traffic is reduced by 30 in scenario sets 1,2, and 3. 17

Figure 10. Scenario 1: Average (Avg.) daily VMT, empty VMT, and CO_2 emissions. 19

Figure 11. Scenario 2: (a) Average (Avg.) daily VMT and CO_2 emission. (b) Average daily empty VMT". 20

Figure 12. Scenario 3: (a) Average (Avg.) daily VMT and average CO_2 emission. (b) average daily empty VMT. 22

Figure 13. Scenario 4: Percentage change in (a) daily total and (b) average (Avg.) VMT and empty VMT. 24

Figure 14. Scenario 4: Daily total CO_2 emission and average CO_2 emission. 25

Figure 15. Parking revenue scenarios. 26

Glossary

Abbreviations

AV	automated vehicle
CBD	central business district
DO	drop-off
Mph	miles per hour
m/s	meters per second
PU	pick-up
TAZ	traffic analysis zone
VMT	vehicle miles traveled

The Impacts of Automated Vehicles on Center City Parking Demand

EXECUTIVE SUMMARY

The potential for automated vehicles (AVs) to reduce parking in city centers has generated much excitement among urban planners (e.g., NACTO, 2017). AVs could drop-off (DO) and pick-up (PU) passengers in areas where parking costs are high: personal AVs could return home or park in less expensive locations, and shared AVs could serve other passengers. Reduced on-street and off-street parking present numerous opportunities for redevelopment that could make cities more livable, for example, by opening more street and sidewalk space for pedestrian and bicycle travel. However, reduced demand for parking would be accompanied by increased demand for on-street DO/PU spaces with related movements to enter and exit the flow of traffic. This change could be particularly challenging for traffic flows in downtown urban areas during peak hours, where high volumes of DOs and PUs are likely to occur. To our knowledge, only a limited amount of research has examined the travel effects of a shift from parking to DO/PU travel and the impact of changes in parking supply.

Our study uses a microscopic road traffic model with local travel activity data to simulate personal AV parking scenarios in San 'Francisco's downtown central business district (CBD). In these scenarios, we vary (1) the demand for DO and PU stops versus parking, (2) the supply of on-street and off-street parking, and (3) the total demand for parking and DO/PU travel due to an increase in the cost of travel to the CBD. The results explore answers to the following questions.

What are the impacts of increasing DO/PU demand relative to parking demand as AVs penetrate the vehicle market?

For the CBD study area, the shift from parking trips to DO/PU trips significantly reduces traffic delay because of avoided parking search travel and more efficient use of parking spaces. While a parked vehicle typically occupies a space for 2 hours, a DO/PU vehicle occupies a space for 20 seconds. At the CBD level, these traffic flow improvements are not off-set by increases in empty passenger VMT and vehicles exiting and entering the flow of traffic for DOs and PUs. However, on roads where the demand for parking and DO/PU spaces is relatively high, the opposite is true. Empty passenger VMT and increased vehicle movements do off-set the travel flow benefits from reduced parking search travel. Empty vehicle travel drives increases in VMT and CO_2 emissions. However, in the early stages of DO/PU market penetration, reductions in parking search travel drive reductions in CO_2 (Figure ES-1).

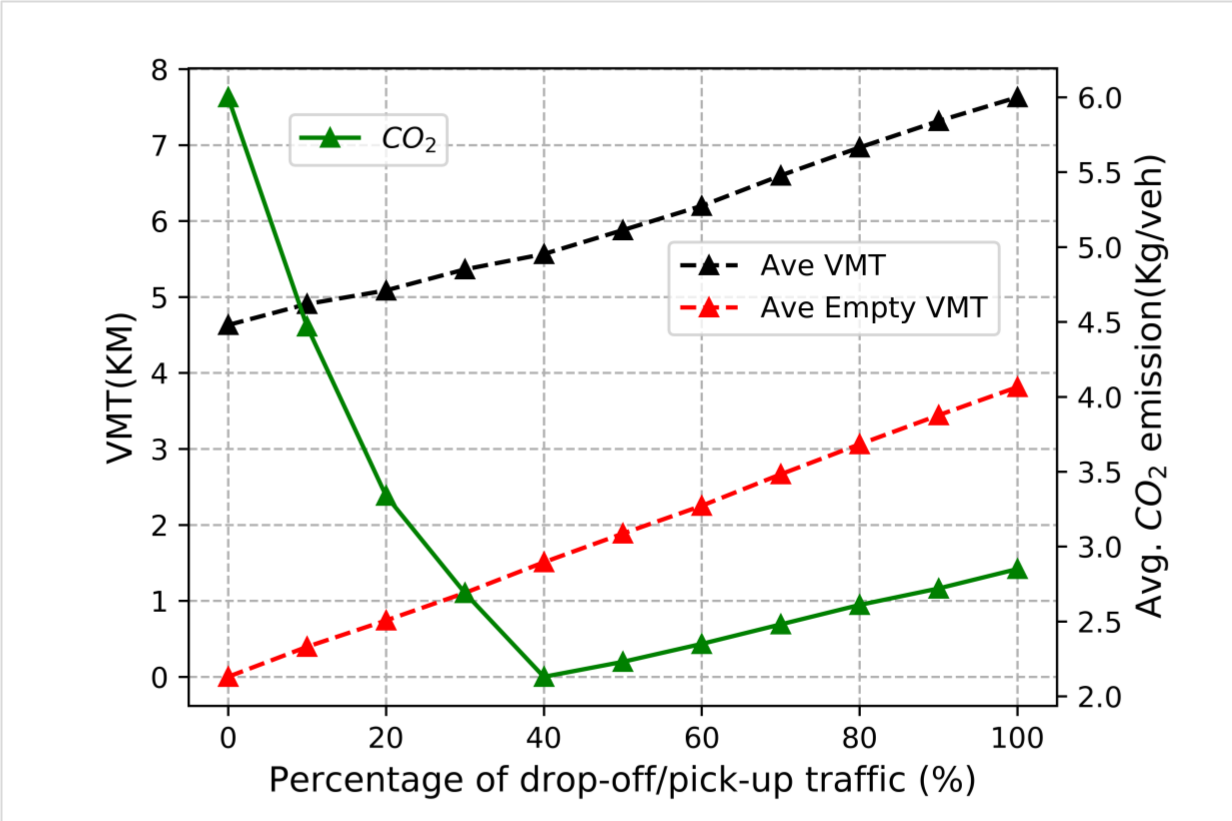


Figure ES-1. Scenario 1: Average (Avg.) daily VMT, empty VMT, and CO_2 emissions.

We also examined changes in parking revenue for this scenario. We found a significant reduction in parking revenues, which could potentially be off-set by charging more than double the average hourly parking rate for a DO/PU event.

Can the conversion of on-street parking spaces to DO/PU spaces address impacts due to increased DO/PU demand?

An improved match between DO/PU demand and DO/PU spaces can reduce traffic congestion, VMT, and CO_2. However, the match must be specific to streets and time of day. An over-allocation of DO/PU spaces can increase parking search and empty vehicle travel, which can increase VMT and CO_2 emissions

It may be possible to redress some negative traffic flow impacts from increasing shares of DO/PU traffic. However, our results show that the conversion of parking spaces to DO/PU spaces must be street specific and dynamic over-time to adjust to changes in AV market shares. Such adjustments would require continuous, detailed roadway monitoring and planning, which may be a challenging task for many US cities.

What are the impacts of concentrating the supply of off-street parking in fewer parking facilities?

Our results show that increasing the concentration of off-street parking supply in fewer locations worsens CBD congestion. Increases in VMT are driven by empty vehicle travel and parking search travel, which, in addition to congestion, also increases CO_2 emissions. Strategies are needed to implement optimally relocate off-street parking capacity.

How might reduced traffic demand that may result from auto pricing policies impact the outcomes for scenarios that increase DO/PU demand, convert on-street parking to DO/PU spaces, and increase the concentration of off-street parking supply?

The 30% reduction in traffic demand in the CBD, which approximates the effects of a significant auto pricing policy, came close to eliminating congestion (as measured by vehicle speed and road occupancy). The change in VMT was relatively proportional to the change in traffic demand across all scenarios. However, the magnitude of congestion reduction CO_2 emissions depended on the size of the congestion problem in the base case for each scenario.

Introduction

The potential for automated vehicles (AVs) to reduce parking in central cities has generated much excitement among urban planners (e.g., NACTO, 2017). AVs could drop-off (DO) and pick-up (PU) passengers in areas where parking costs are high: personal AVs could return home or park in less expensive locations, and shared AVs could serve other passengers. Reduced on-street and off-street parking present numerous opportunities for redevelopment that could improve the livability of cities, for example, by opening more street and sidewalk space for pedestrian and bicycle travel. However, reduced demand for parking would be accompanied by increased demand for on-street DO/PU space with related movements to enter and exit the flow of traffic. This change could be particularly challenging for traffic flows in downtown urban areas during peak hours, where high volumes of DOs and PUs are likely to occur. To our knowledge, only a limited amount of research has examined the travel effects of a shift from parking to DO/PU travel and the impact of changes in parking supply. This study uses a microscopic road traffic model with local travel activity data to simulate AV parking scenarios in San Francisco's downtown central business district (CBD). In these scenarios, we vary (1) the demand for DO and PU travel versus parking, (2) the supply of on-street and off-street parking, and (3) the total demand for parking and DO/PU travel due to an increase in the cost to travel to the CBD.

Literature Review

Few studies address the effects of increased DO and PU travel from the introduction of AVs. Two studies, however, indicate that the potential to reduce the amount of land developed for parking may be significant. Zhang and Guhathakurta (2017) simulate parking demand for a fleet of autonomous taxis in Atlanta (GA) and find that land devoted to parking could be reduced by 4.5% once the fleet began to serve 5% of trips and could reduce 67% of parking lots in the CBD.

Martinez et al. (2015) simulate a fleet of automated taxis (100% market penetration) with and without sharing (taxi with 1+ passenger) and transit, in Lisbon, Portugal, and find that the share of baseline parked vehicles is 89% to 94%. At 50% market penetration levels, supportive transit policies must be in place to significantly reduce the share of baseline parked vehicles (24% and 21%, respectively, with and without sharing).

Another study examines the relationship between the location and cost of parking facilities and personal AV empty-vehicle relocation travel (Correia et al., 2016). It provides insight into the potential magnitude of the parking-related AV travel problem. The authors use an agent-based model that represents mode choice and dynamically assigned route choice with parking and repositioning travel in Delft, Netherlands, which is a small city in South Holland. The model uses roadway and transit networks, mode choice coefficients, and generalized cost functions. The authors find that paid parking significantly increases empty vehicle relocation travel, VMT, and vehicle hours of delay and reduces car mode share and total vehicle parking time. Widespread increases in parking prices produced the largest increase in VMT and empty VMT (325% and 87.4%, respectively) and the greatest decline in total vehicle parking time (8.7%). Congestion or vehicle hours of delay grew the most (824%) when there was a charge for parking everywhere except for two peripheral lots. Overall, the share of repositioning travel ranges from 11% to 65%; the rise in car mode share ranges from -26 to 31 percentage points; VMT grows from 17% to 325%; vehicle hours of delay increases from 20% to 699%; and total vehicle parking time ranges from -7% to 25%.

Millard-Ball (2019) uses data from the San Francisco City and County Travel Demand Model and shows that AVs will encourage vehicle travel due to vehicles cruising and avoiding parking, ultimately increasing congestion and VMT. The study evaluates three strategies to avoid parking policies for AVs with 100% AV market penetration: allowing AVs (1) to park in peripheral areas where parking is free or low cost; (2) to drive home after dropping passengers off; and (3) to cruise on roads after dropping passengers off until they need picking up again. The author evaluates these alternatives with a ""pgrouting"" software package that calculates the direct distance between origin traffic analysis zones (TAZs) and destination TAZs and does not consider the effects of traffic congestion. The current study uses a microscopic traffic simulation model that considers congestion and evaluates the incremental shifts to 100% AV market penetration.

Methodology

Modeling

We selected the microscopic road traffic model (Simulation of Urban MObility or SUMO) to simulate the traffic flow effects of the AV scenarios in this study. SUMO is an open-source, highly portable, multimodal, microscopic road traffic simulation package designed to handle large road networks (Behrisch et al., 2011). The SUMO model in this study uses local travel activity data from the San Francisco Bay Area MATsim (SFBA-MATsim) model (Horni et al., 2016; Rodier et al., 2018; Jaller et al., 2019). The SFBA-MATSIM model was developed and calibrated with the official San Francisco Bay Area Metropolitan Transportation 'Commission's Activity-Based Travel Demand Model (MTC-ABM).

The geographic focus of this study is the City of San Francisco's CBD (see Figure 1). We selected individual daily activity tours with at least one vehicle stop in San 'Francisco's CBD from the SFBA-MATsim model. Arrival and departure times for vehicle tour stops are in increments of seconds in the SFBA-MATsim model. We also converted transit trips to AV trips for the purpose of the simulation. From the SFBA-MATsim model, we identified about 900,000 travelers who made 1.8 million trips. One percent of these are internal to the study area, and the remainder had at least one stop in the study area. Total simulated vehicle trip volumes in the network were adjusted to match roadway supply (see discussion below), transit supply, and model year congestion levels.

The SUMO simulations assume that both on-street parking and DO/PU events will take place at the on-street at the curb (i.e., no vehicle can double park for even a short period). We add intermediate stops in SUMO to convert trips that end or begin with parking to DO/PU trips. The dwell time for DO/PU events at the curb is assumed to be 20 seconds. SUMO represents vehicle movements, including lane merging and exiting, necessary to park a vehicle or DO/PU passengers. SUMO directs vehicles to available parking spaces closest to their destinations. However, if another vehicle has secured the nearest space, then SUMO will re-direct the vehicle to the next nearest parking space within the traffic analysis zone (see below) in which the destination is located. If at some point, vehicles occupy all on-street parking spaces in the traffic analysis zones, then vehicles that are trying to park and DO/PU a passenger will stop in the street and wait for an on-street parking space to open up. Note that this is an extremely rare occurrence in our model simulations, and future research should improve the representation of vehicle reactions to zero parking occupancy in a zone. This behavior will tend to cause traffic to backup and cause congestion. Similarly, SUMO will direct vehicles that seek off-street parking to the nearest off-street facility until the facility is filled, after which it will direct them to the next closest off-street parking facility. This process will continue until all the off-street parking facilities in the network are full. Once this occurs, vehicles will stop and start queuing in the street(s) that lead to off-street parking facilities, which will backup traffic and cause congestion.

Travel activity patterns (and trips) are held constant in the scenarios despite changes in congestion. Thus, scenarios that increase congestion will not see reductions in the demand for travel, parking, and DOs/PUs in the CBD. Similarly, scenarios that reduce congestion will not increase the demand for travel, parking, and D.O./PUs in the CBD.

The scenario simulations assume the use of personal automated vehicles (or personal AVs) as opposed to shared AVs. Personal vehicles are owned or leased by a household for personal or family use and not used by other travelers. As a result, after the vehicle drops-off the passenger, the vehicle will exit the study area to return home or service another family member. However, the empty-vehicle travel calculated for this study includes only the distance and time required to exit the study area.

On-street parking location and DO/PU events in SUMO are determined by vehicle-specified "stops" that include a start position and an end position as link coordinates. For example, suppose we identify a 100-meter length of curb along a link and allocate the length from the 50- to 100-meter marks for DOs/PUs. If there is no other vehicle in this zone along the curb, a vehicle needing curb space for a DO/PU will park at the 100-meter mark and, if the vehicle is 5 meters long, it will occupy the space at the 95- to 100-meter mark. The maximum ""capacity" of the on-street parking is the link length divided by vehicle length. SUMO also allows for off-street parking with its customized parking area definition to simulate garage parking or parking lots. The user specifies the vehicle start and end position, parking capacity, and parking space angle (see SUMO Documentation[1] for more details).

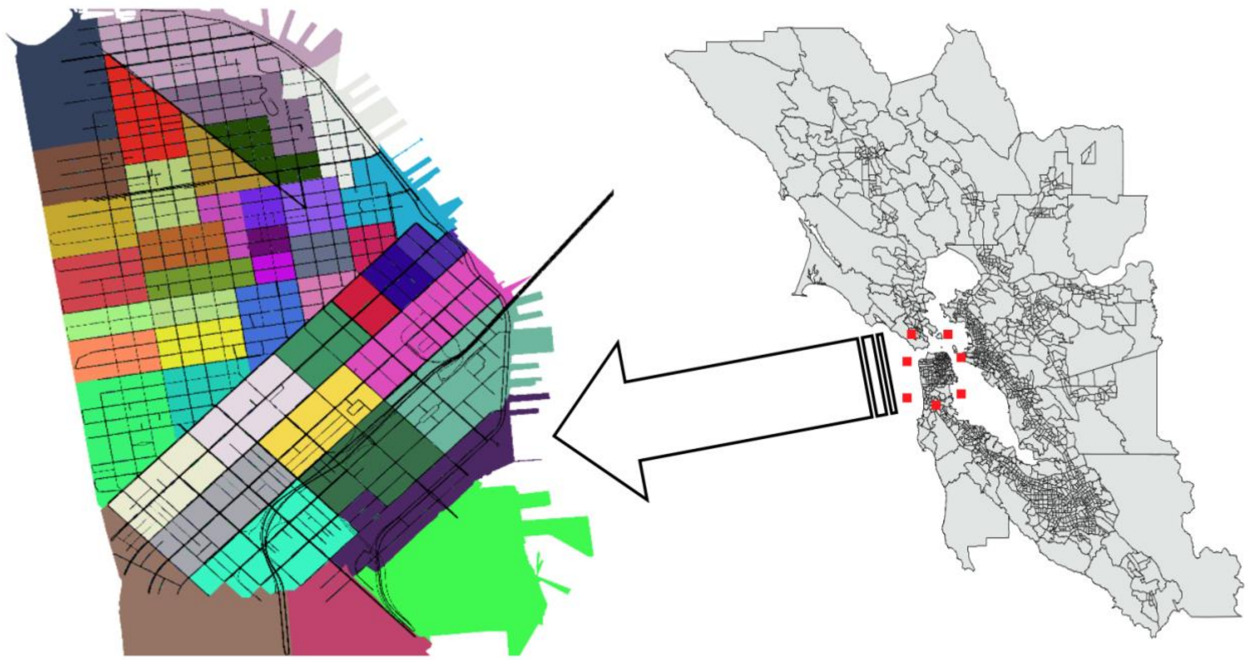
Network and Traffic Analysis Zones

The SUMO simulations use transportation analysis zones (TAZ) that are consistent with the MTC-ABM and SFBA-MATsim 'models' zone system. In Figure 1(a), the different colors depict separate TAZs. The TAZs in the study area are among the smallest in the region and include census blocks. For this specific network, there are 45 TAZs in total. In Figure 1(b), we show the

[1] http://sumo.dlr.de/wiki/Simulation/ParkingArea

TAZ map for the entire San Francisco Bay Area from which we identified individuals and trips that traveled into, out of, and through the study area in Figure 1(a), as described above.

We used the SUMO network editor to import OpenStreetMap for the San Francisco CBD roadway network. We edited the OpenStreetMap roadway network to exclude minor roads. Major roads in the CBD were included in the final network to increase the efficiency of SUMO simulations.



(a) (b)

Figure 1. (a) Study area: Central Business District for the City of Francisco. (b) Traffic Analysis Zones for MTC-ABM Model.

Parking Supply Data

The San Francisco Parking Census is the source of the parking supply data used in this study.[2] The San Francisco Municipal Transportation Agency (SFMTA) collected the parking supply data: 97% through field surveys and 3% through remote resources. The on-street parking supply in the dataset includes metered on-street spaces, non-metered demarcated spaces (parking stalls), and non-metered un-demarcated spaces (unmarked curb length). For non-metered spots, we apply a standard 17 feet per parking space, which is the length needed by an average sedan to park between two vehicles. When a curb space was short and could support only one vehicle, we used 12 feet as the length of the parking spot. For any unmarked perpendicular

[2] http://sfpark.org/resources-overview/

parking, we used a standard of 8 feet and 6 inches of curb space. We did not include controlled parking and restricted parking spaces in the data set.

The data set included 1,351 on-street parking locations with a total capacity of 20,019 parking spots within the study area. For off-street parking, there are 356 locations with a total capacity of 65,404 parking spots. The spatial data were edited and processed using ArcGIS and the SUMO spatial analysis tool.

Parking Revenue

The substitution of DO/PU events for parking will tend to reduce parking revenues. To understand the magnitude of the reduction, we calculate net parking revenues for the scenarios simulated in this study. Parking costs are assumed to be $1.00 per 15 minutes for on-street parking and $4.00 per hour for off-street parking. Total scenario parking revenue is calculated by summing the costs of each on- and off-street parking event.

Emissions Impact Modeling

We calculate how each of the different AV scenarios will affect CO2 emissions within the study area. We use the default emission model[3] defined in SUMO to evaluate vehicle emissions CO2 (kilograms). CO2 emissions are a common proxy for greenhouse gas emissions. The model uses the fitted variables from HBEFA3 (Handbook emission factors for road transport version 3) in the following function:

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

where v is the vehicle speed, and a is the acceleration/deceleration rate. For the details of how SUMO implemented this model, please refer to SUMO documentation.[4]

Scenarios

Four sets of scenarios are simulated with SUMO and evaluated for traffic flow, VMT, and CO_2 emission effects in San Francisco CBD with personal AVs. Simulation of shared AVs (for pooled or individual rides) AVs was not possible with a model set that could evaluate microscopic traffic impacts of changes in parking demand in an actual CBD. Future research should examine the effects of similar scenarios with shared AVs. However, at this point, it is not clear whether shared and/or personal automated vehicles will dominate future vehicle markets. The following describes the scenario sets and their simulation in SUMO (see also Table 1 below):

- **Scenario Set 1: What are the impacts of DO/PU demand relative to parking demand as AVs penetrate the vehicles market?** We simulate a base case scenario in which 100% of simulated trips park and gradually increase the share of DO/PU trips in 10% increments until 100% of trips end by dropping-off passengers and begin with picking-up

[3] https://sumo.dlr.de/docs/Models/Emissions/HBEFA3-based.html; https://www.hbefa.net/e/index.html
[4] https://sumo.dlr.de/wiki/Models/Emissions

passengers. Travel activity (i.e., the number of trips by time-of-day and origin and destination locations) is held constant. Vehicle trips with purposes that involve long stays (greater than 2 hours) in the study area park in off-street parking facilities closest to their destination at the time of arrival. Vehicles with shorter stays (less than 2 hours) are allocated to on-street parking closest to their destination at the time of arrival.

- **Scenario Set 2: Can the conversion of on-street parking spaces to DO/PU spaces meet the increasing DO/PU demand caused by a shift to AVs?** In this scenario set, on the supply side, we incrementally convert on-street parking to DO/PU spaces, as represented in our study area parking inventory, while holding travel activity constant. We use 80% demand for parking and 20% for DO/PU. The locations for converted parking to DO/PU areas are randomly selected within the study area.
- **Scenario Set 3: What are the impacts of concentrating the supply of off-street parking in fewer parking facilities?** AV technology, as described in our literature review above, is expected to increase the capacity of existing off-street parking facilities. Scenario set 3 uses the 50% DO/PU traffic scenario from scenario set 1 without any dedicated DO/PU spaces. We randomly select parking spaces from off-street parking facilities to relocate to other off-street parking facilities. The relocated shares increase from 10% to 90% in the scenario set. Total off-street parking supply and demand remain constant across the scenarios.
- **Scenario Set 4: How might plausible reductions in traffic demand in the study areas from auto pricing policies impact the outcomes for scenario sets 1 to 3, above?** A 30% random reduction in traffic is simulated with the (a) 100% on-street parking, and 0%DO/PU traffic shares in scenario set 1; (b) 50% on-street parking and 50% DO/PU traffic shares (i.e., demand) with a 50% shift from on-street parking spaces to DO/PU spaces (i.e., supply) from scenario set 2; and (c) 50% on-street parking and 50% D.O./pick up traffic shares with a 30% increase in the concentration of off-street parking from scenario set 3.

Table 1. Summary of Study Scenarios

	Scenario Set 1	Scenario Set 2	Scenario Set 3	Scenario Set 4
Description	AVs shift demand from parking to DO/PU.	Convert parking spaces to DO/PU spaces to match need.	Off-street parking is concentrated in fewer facilities.	Pricing policies reduce CBD traffic.
On-Street Parking Demand	100% to 0% (10% increments)	80%	50%	Applied to scenario sets 1, 2, and 3.
DO/PU Demand	0% to 100% (10% increments)	20%	50%	
Off-Street Parking Demand	Constant	Constant	Constant	
On-Street Parking Supply	Constant	100% to 0% (10% increments)	Constant	
DO/PU Supply	Constant	0% to 100% (10% increments)	Constant	
Off-Street Parking Supply	Constant	Constant	Reallocate initial distribution to fewer locations: 10% to 90% (10% increments)	
Traffic Activity	Constant	Constant	Constant	30% reduction

Results

Traffic Flow Results

Scenario Set 1: What are the traffic flow impacts of increasing DO/PU demand relative to parking demand as AVs penetrate the vehicles market?

Figure 2 shows the average speeds by time of day in meters per second (m/s) for the CBD as the share of DO/PU traffic increases from 0% to 100% in 10% increments. The fastest travel speed (or free-flow) simulated for this area is 8 m/s (~18 mile per hour [mph]). From 6 am to 7 am, when travel activity is light, the change in the share of vehicles parking and dropping-off/picking-up has almost no effect on travel speeds. As travel activity increases and decreases throughout the day, speeds go as low as 1 m/s (or about 2 mph) during the mid-day period in the 0% scenario (all vehicles park) and increase rapidly to free-flow speeds (8 m/s or 18 mph) when DO/PU trips substitute for 40% to 50% of parking trips. In sum, on average for the CBD, the shift to DO/PU trips from parking trips improves traffic flow because of reduced parking search time and more efficient use of parking spaces (i.e., instead of parking in a space for two hours, vehicles pull-over for 20 seconds for a DO/PU). These traffic flow improvements are not off-set by increases in empty passenger VMT and vehicles exiting and entering the flow of traffic to drop-off and pick-up passengers.

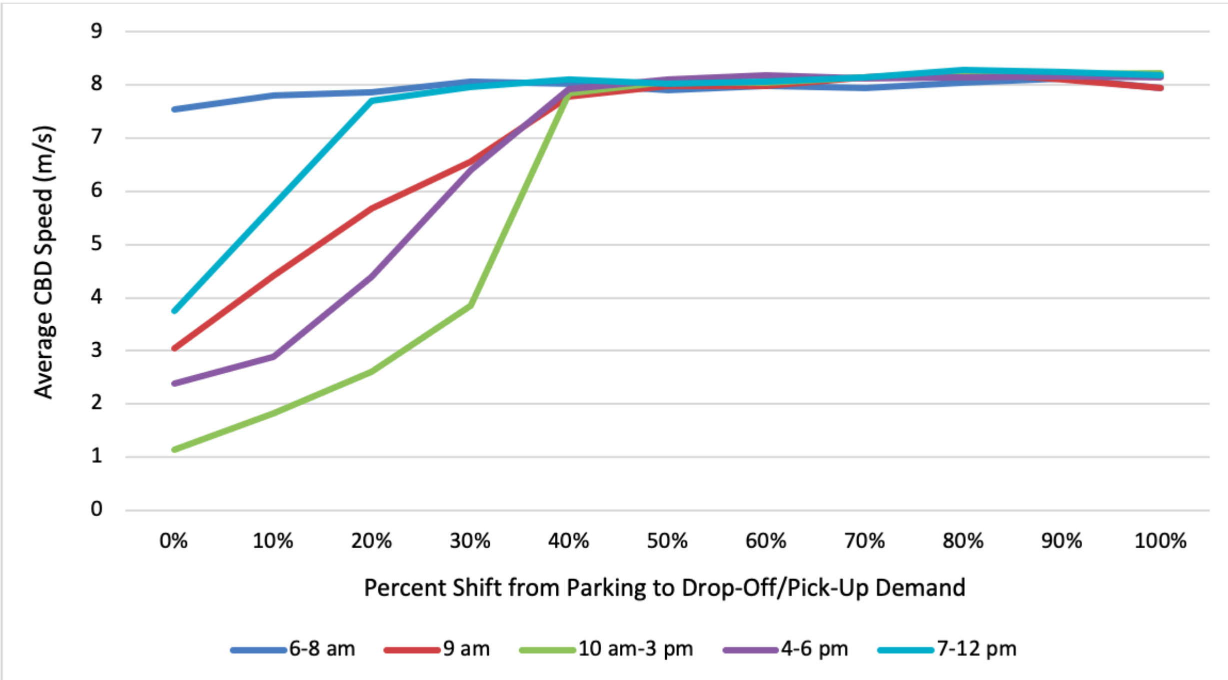


Figure 2. Average CBD speed (m/s) by the time of day, as the share of drop-off/pick-up demand substitutes for parking demand from 0% to 100% in 10% increments (Scenario Set 1).

However, when we consider the roadway link-level results for the same scenario, the findings are very different. Links refer to a road segment. On roads where demand for parking spaces is high, empty passenger VMT and vehicles moving in and out of lanes for DO/PU travel do off-set the travel flow benefits from reduced parking search travel. Figure 3 shows the change in roadway link-level occupancy for the CBD network with increasing shares of DO/PU trips with 0%, 50%, and 100% DO/PU traffic. Low vehicle to roadway vehicle occupancies are light green and represent "free-flow" vehicle speeds, as described above, and high vehicle occupancies are red (approaching 1.0) and represent congested conditions and very low vehicle speeds.

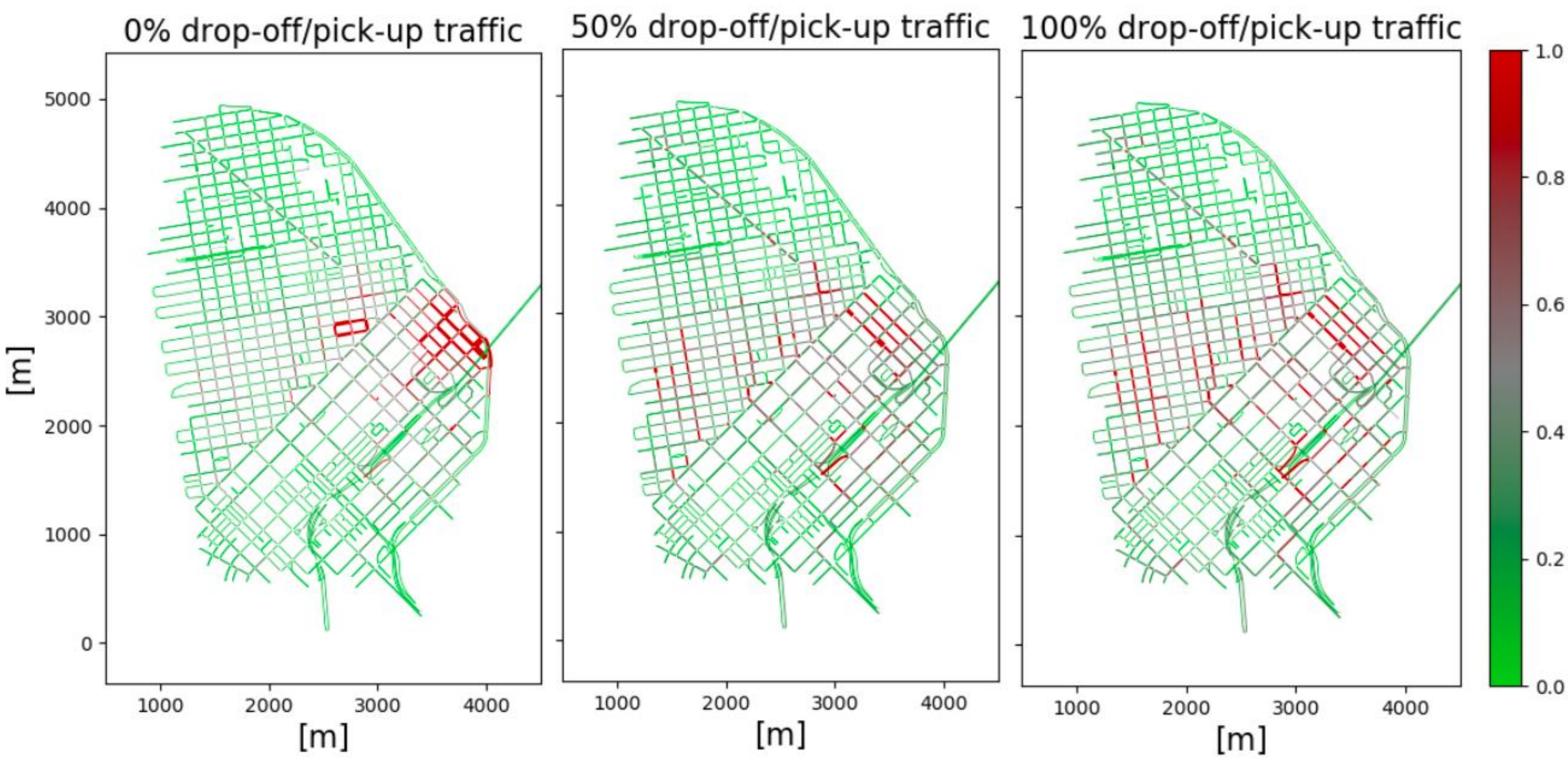


Figure 3. Average daily roadway link-level occupancy results for scenario set 1 (0%, 50%, and 100% shift from parking traffic to drop-off/pick-up traffic). X- and y-axis values indicate meters [m] from an arbitrarily located reference point.

Scenario Set 2: Can the conversion of on-street parking spaces to DO/PU spaces address traffic flow impacts due to increasing shares of DO/PU demand?

Figure 4 shows the percentage change in average CBD speeds by hour of the day for different scenarios with an increasing reallocation of parking spaces to DO/PU spaces, from 20% to 100% (in 20% increments for clarity of presentation). The results show that the 20% shift (blue curve) from parking spaces to PU/DO areas, compared to higher percentages shifts (> 20% to 100%), generally is associated with the highest average speeds in the CBD.

Figure 4 also shows the variability of performance across the scenarios by the time of day. Conversions locations (i.e., parking to DO/PU) were not selected based on high-levels of parking occupancy and DO/PU traffic. Instead, we randomly chose the locations, and this explains the variability.

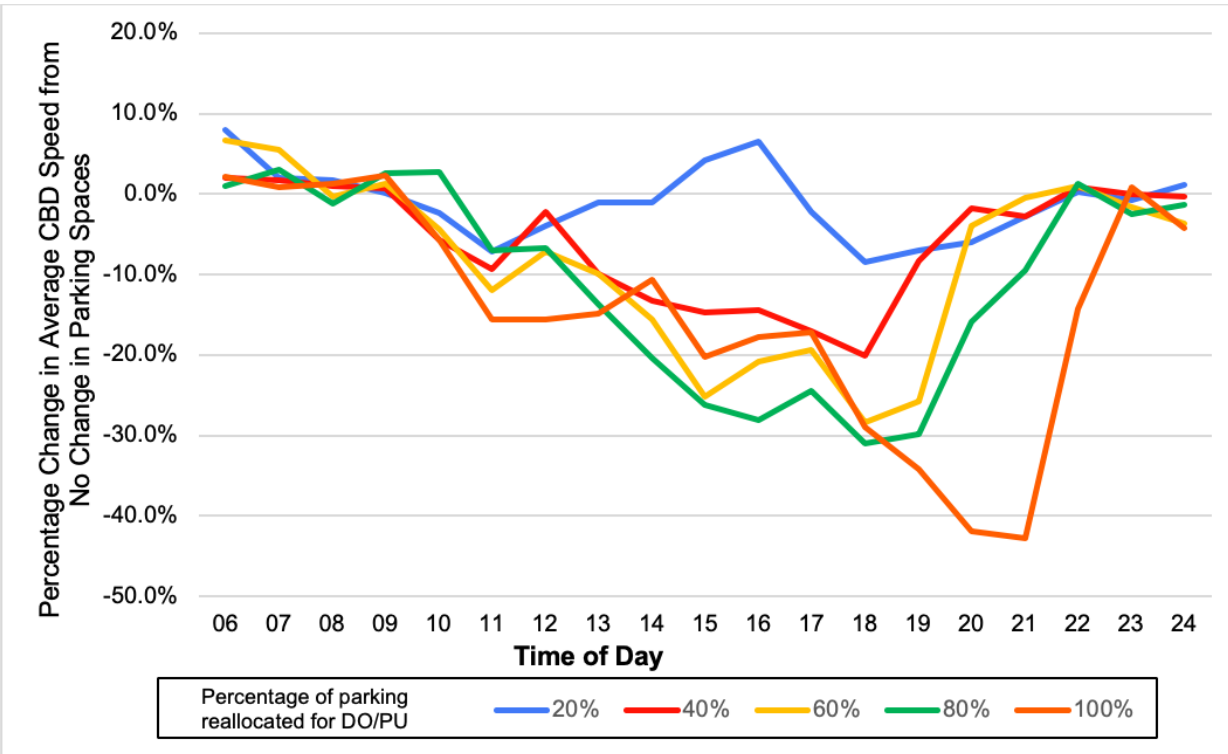


Figure 4. Percentage change in average CBD speed at different times of the day if different percentages of on-street parking spaces (20–100%) are reallocated to drop-off/pick-up spaces.

The need to optimize the transition of parking to DO-PU areas is illustrated further by Figure 5 below, which depicts road level occupancy rates at 20%, 60%, and 100% conversion levels. A visual inspection shows no real difference in congestion at the average daily roadway link level. In sum, these results show that the conversion of parking spaces to DO/PU zones must be dynamic over-time as AV market shares increase and based on continuous, detailed roadway monitoring and planning, which may be a challenging task for many US cities.

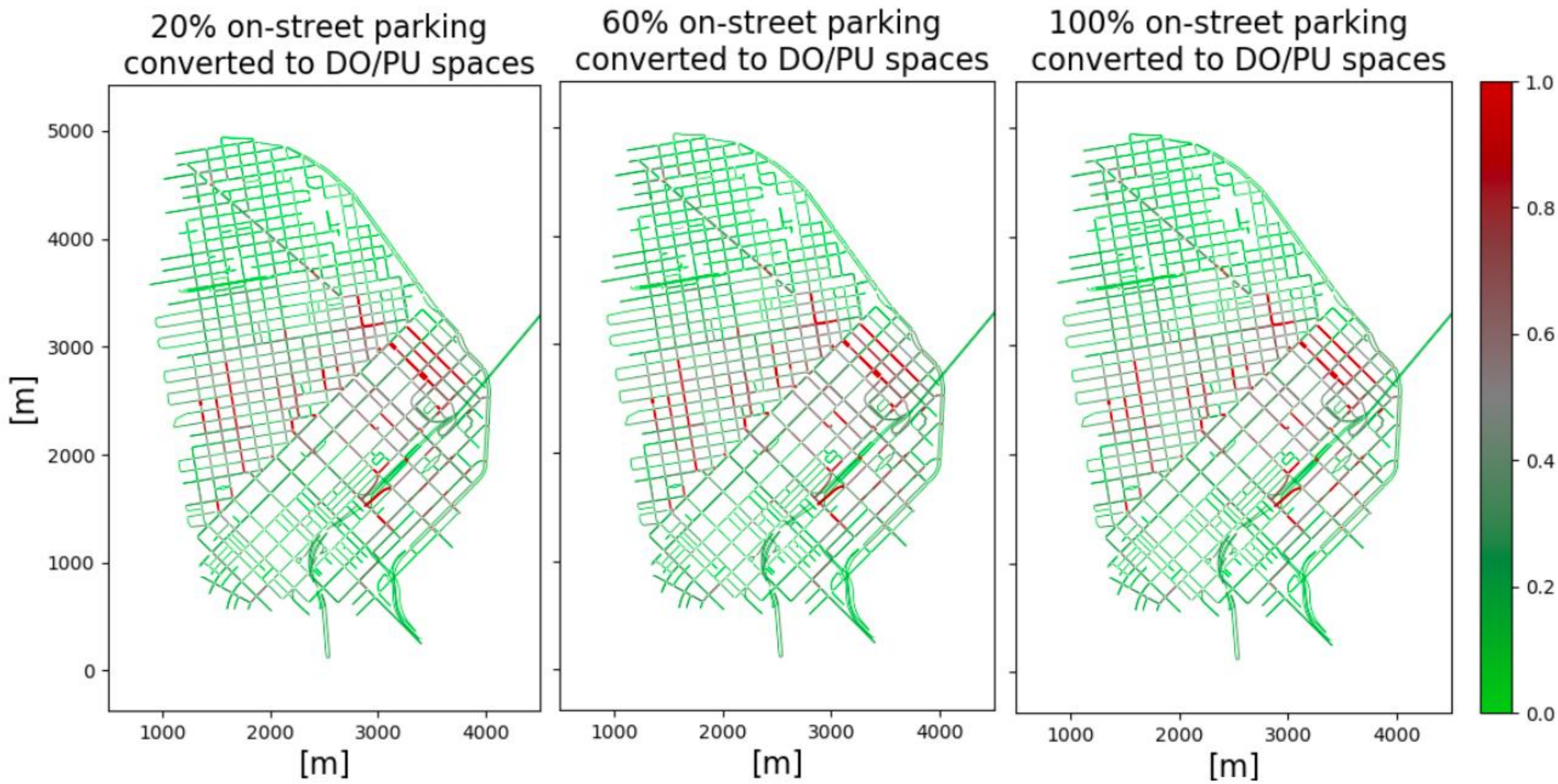


Figure 5. Average daily roadway link-level occupancy results for scenario set 2 (20%, 60%, and 100% of on-street parking spaces converted to drop-off/pick-up spaces).

Scenario Set 3: What are the traffic flow impacts of concentrating the supply of off-street parking in fewer parking facilities?

Figure 6 below depicts average CBD speeds (m/s) by the hour of the day as the distribution of off-street parking supply is concentrated in fewer, randomly selected, off-street facilities. Note Figure 6 shows results in 20 percentage point increments for clarity of presentation. The results indicate that a large concentration of off-street parking supply will significantly reduce average CBD network speeds throughout most of the day The magnitude of the relocation does not have a consistent direct or indirect relationship with the average CBD speed: for example, a 40% reallocation (green curve) leads to higher average CBD speeds than do lower (20%) and higher (60% and 80%) percent reallocations. This lack of a consistent quantitative relationship may be a result of the random locations selected in the model for concentrating off-street parking facilities.

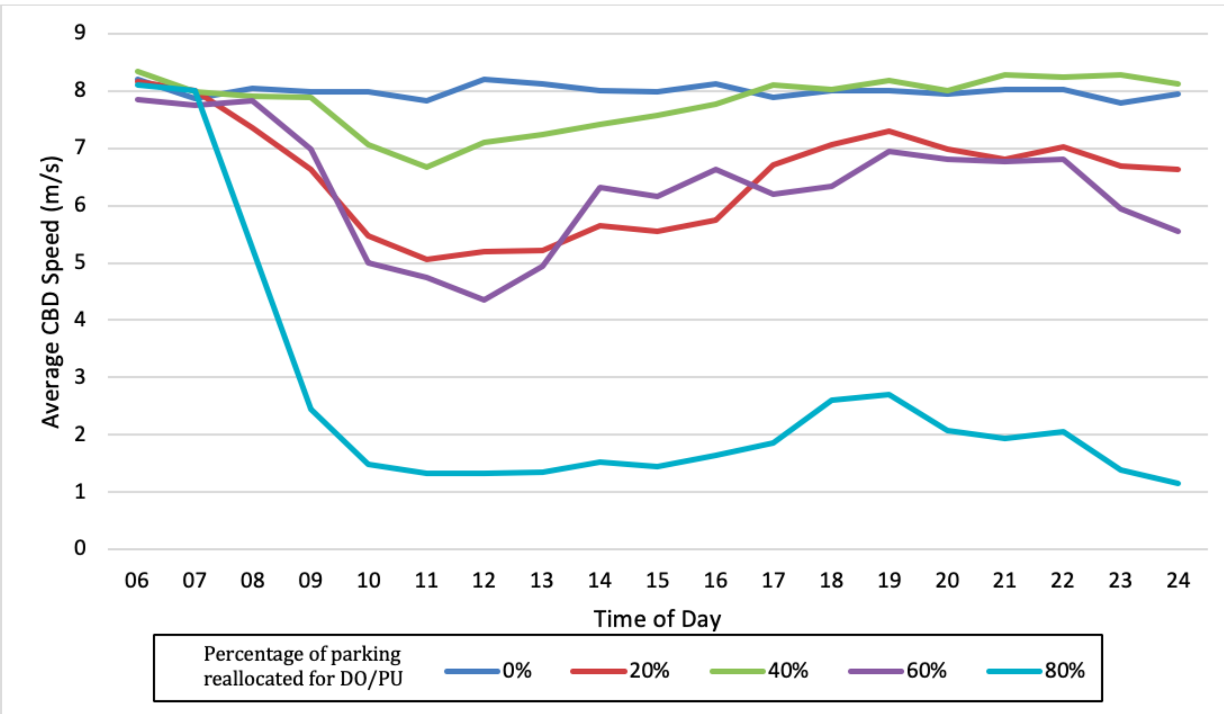


Figure 6. Average CBD speed (m/s) by the hour of the day with the distribution of off-street parking supply concentrated in randomly located, fewer off-street facilities (Scenario Set 3).

Figure 7 shows increasing congestion at the roadway link-level as off-street parking supply is concentrated in fewer locations at 20%, 40%, and 80% relocation levels. We can see signs of significant queuing to enter off-street parking facilities in the 80% scenario.

In sum, these results suggest that an increased concentration of off-street parking supply in few locations can significantly impact congestion levels in the CBD, which indicates the need to examine optimal relocation strategies for off-street parking.

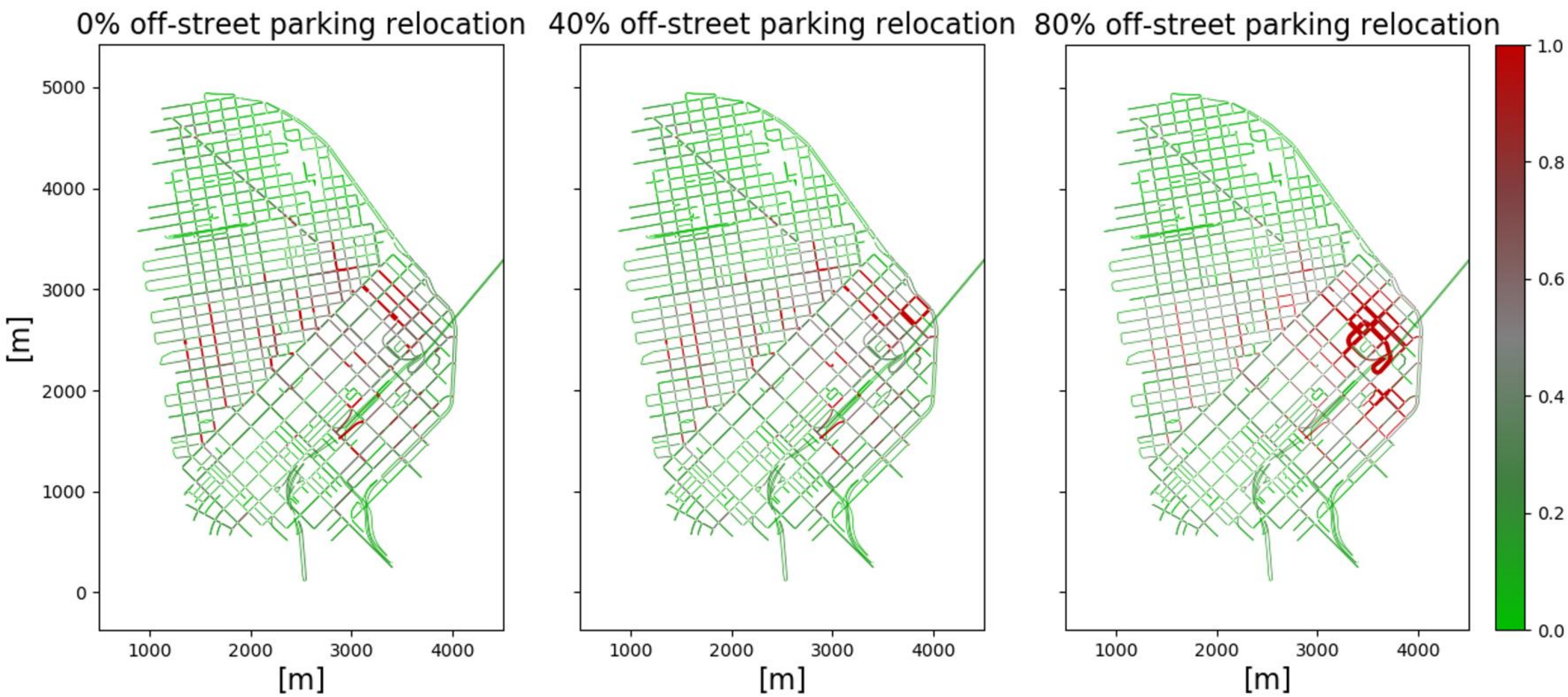


Figure 7. Average daily roadway link-level occupancy results for scenario set 3 (conversion of 0%, 40%, and 80% of on-street parking spaces to drop-off/pick-up spaces).

Scenario Set 4: How might plausible reductions in traffic demand in the study areas from auto pricing policies impact the outcomes for scenario sets 1 to 3, above?

Figure 8 shows the percentage change in average hourly CBD vehicle speeds when traffic is reduced by 30% in scenario sets 1, 2, and 3. There are relatively large changes in average hourly CBD speeds during the peak periods in both scenario set 1 and 2, but improvements are more modest in scenario set 3. Similarly, the average roadway link-level occupancy maps in Figure 9 show more pronounced decreases in occupancy in scenarios 1 and 2 and somewhat less pronounced decreases in scenario set 3. Less traffic in scenario sets 1 and 2 reduce on-street parking search travel and lane entering and exiting movement by DO/PU travel. In scenario set 3, vehicles travel farther to access off-street parking, but queuing to enter facilities appears less severe, with the reduction in overall traffic.

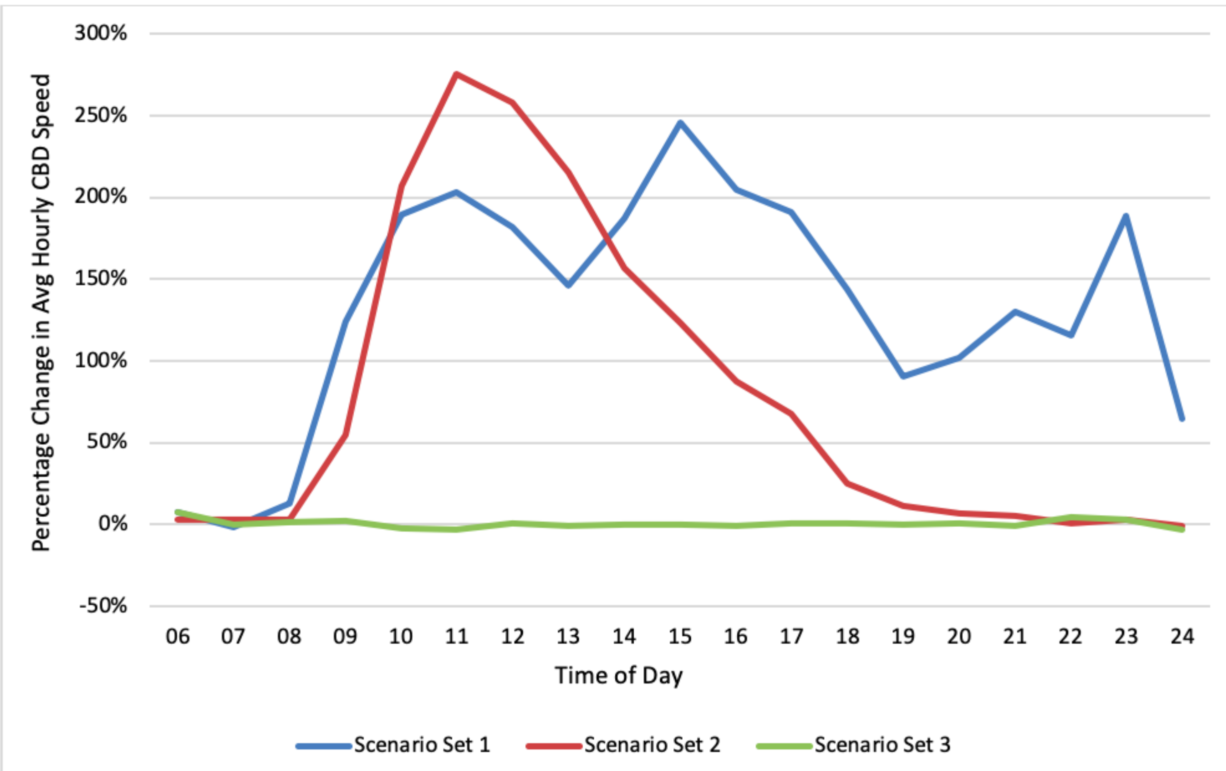
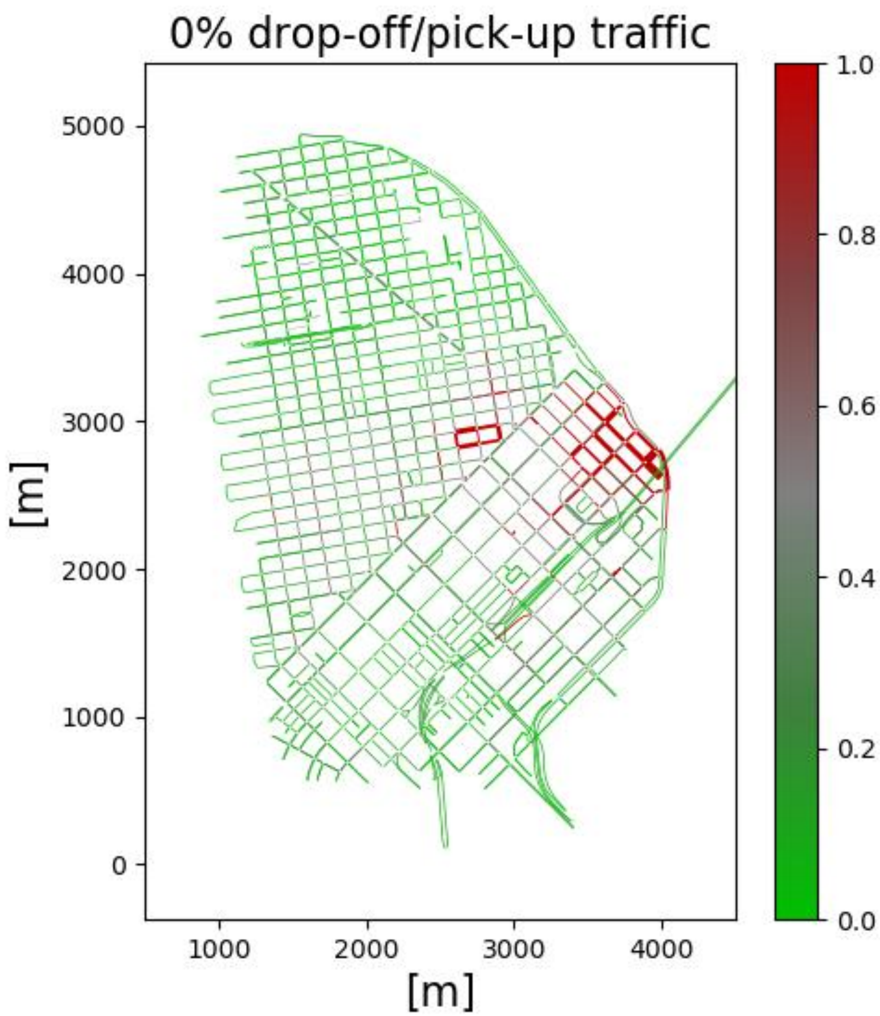
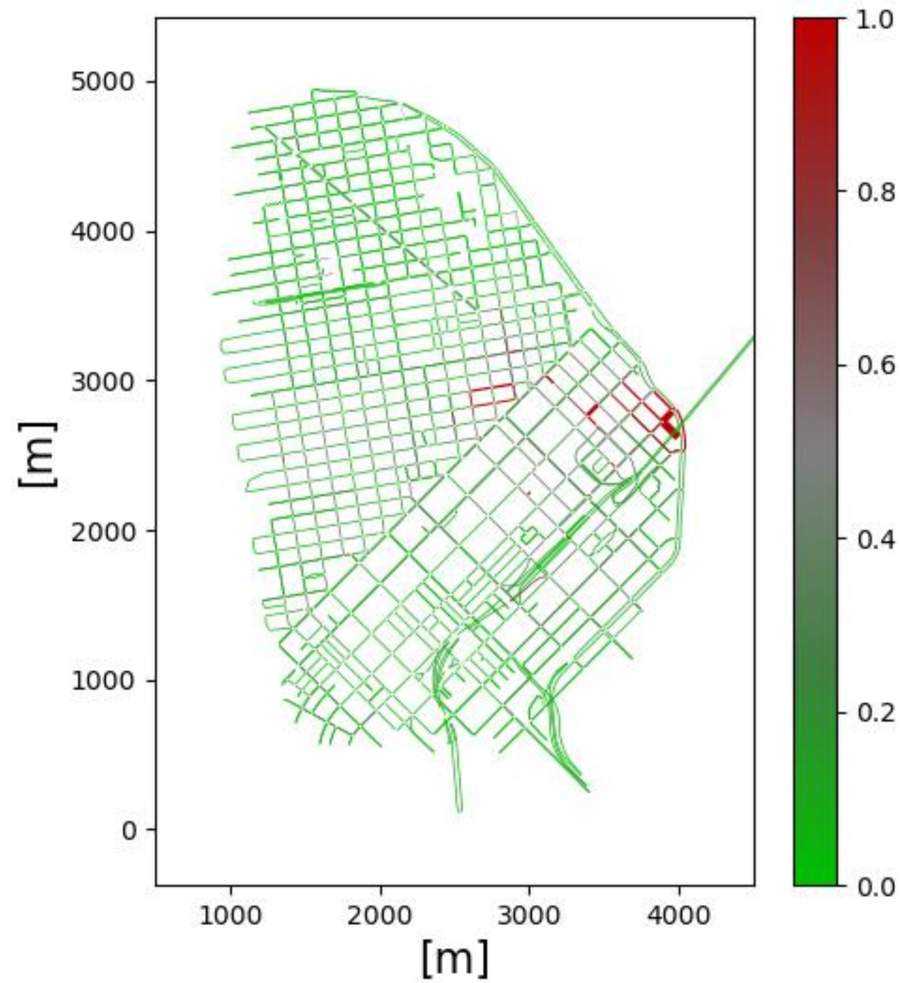


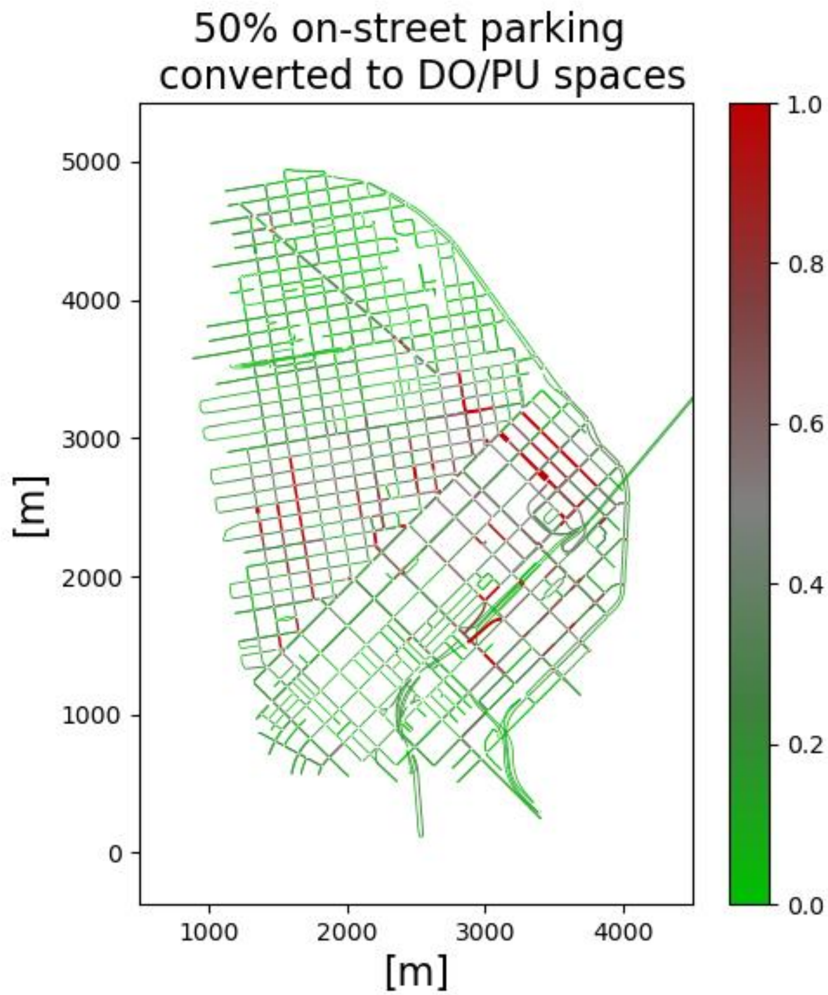
Figure 8. Percentage change in average hourly CBD vehicle speeds if traffic is reduced by 30% in scenarios 1, 2, and 3.



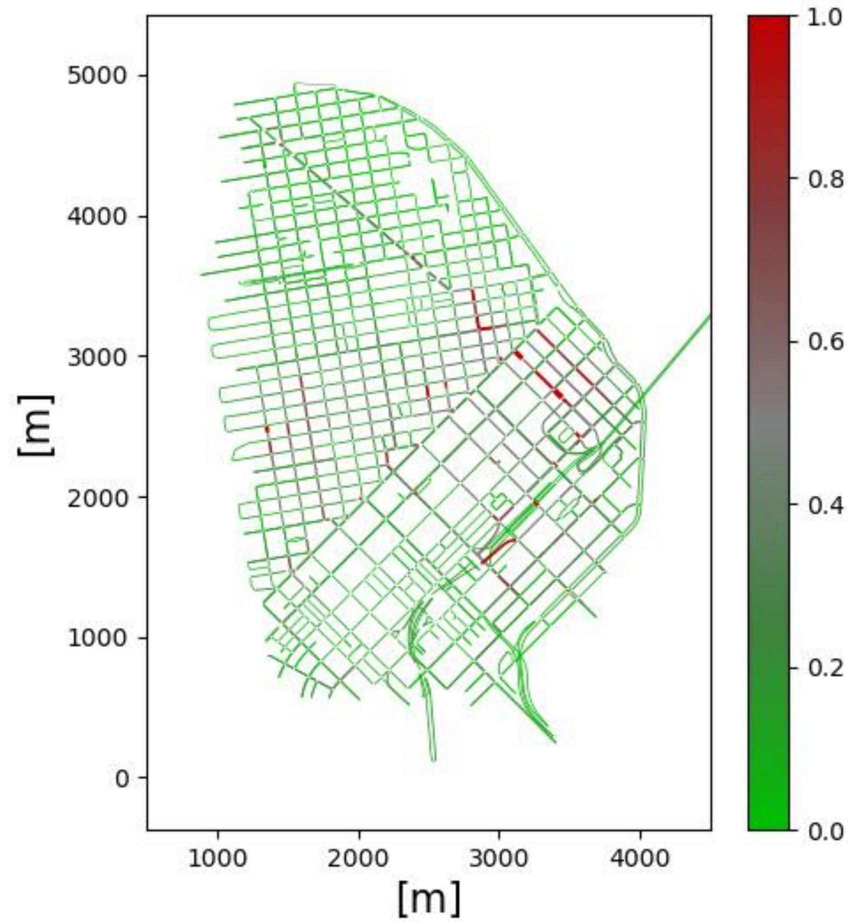
Scenario Set 1



30% traffic reduction in Scenario Set 1

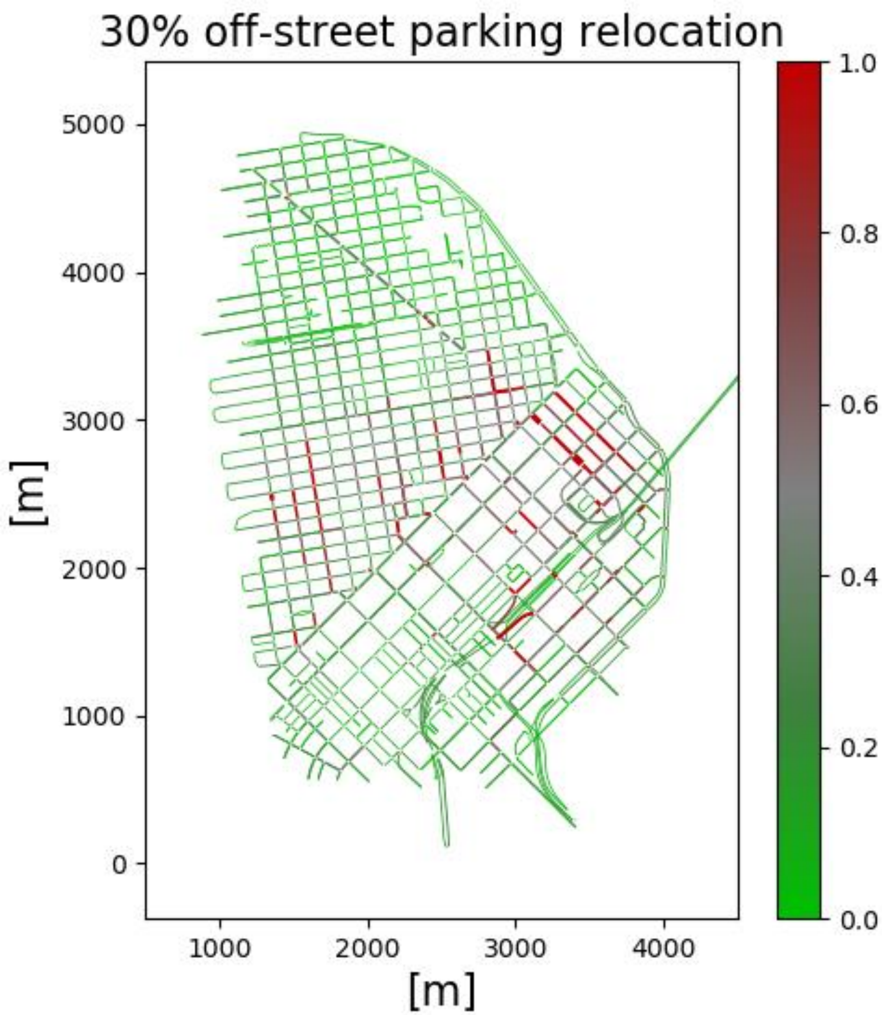


Scenario Set 2

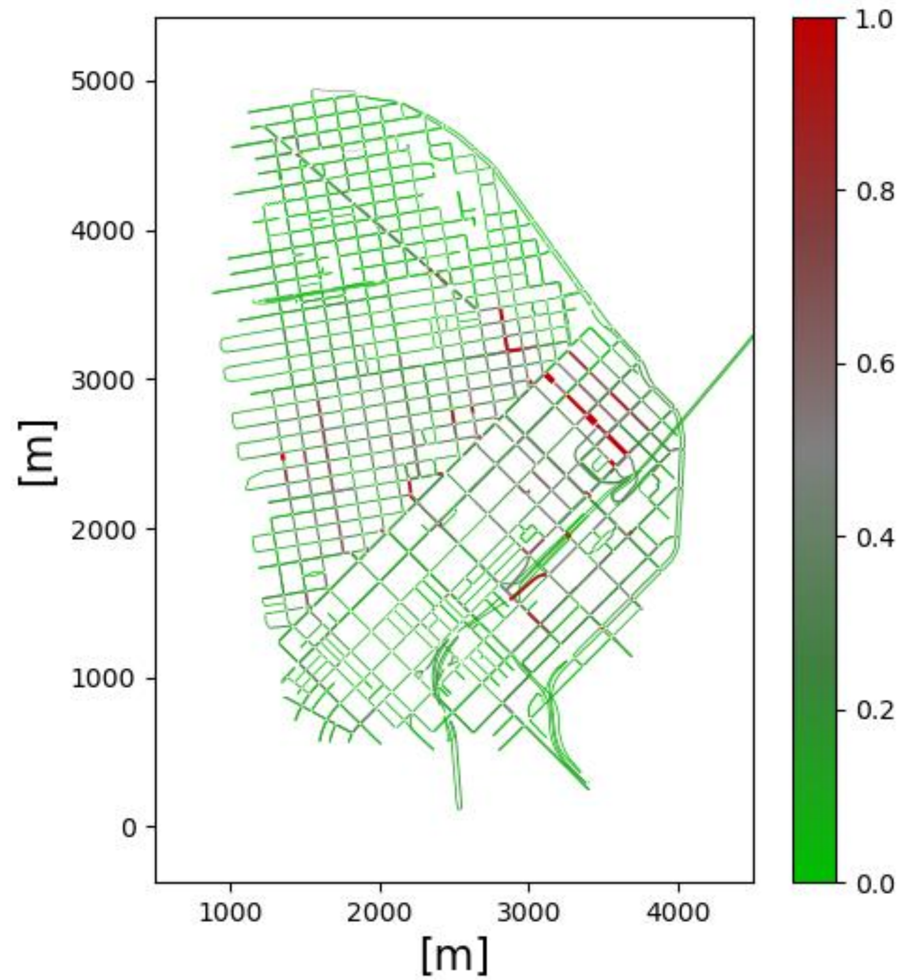


30% traffic reduction in Scenario Set 2

NCST



Scenario Set 3



30% traffic reduction in Scenario Set 3

Figure 9. Average daily link-level road occupancy when traffic is reduced by 30 in scenario sets 1,2, and 3.

VMT and Emission Results

As discussed above, traffic caused by increased DO/PU demand will potentially increase VMT. In this section, we show the impact of AVs using on-street curb space on the overall VMT under different scenarios. We look at the average VMT and average empty VMT within the study area.

Scenario Set 1: What are the VMT and emissions impacts of increased DO/PU demand relative to parking demand as AVs penetrate the vehicle market?

Figure 10 shows the average VMT and empty VMT in the network for different percentages of DO/PU traffic. The average VMT and empty VMT is very close to a linear relationship with the percentage of DO/PU traffic. As the percentage of DO/PU traffic increases, the average VMT and empty VMT also increase. When the DO/PU percentage increases from 0% to 100%, the average VMT increases monotonically by approximately 70%. Empty VMT has a very similar pattern. Empty VMT drives the increase in VMT as AVs drop-off and pick-up passengers. A small part of empty VMT is from extra "parking search" trips caused by higher levels of congestion. The contribution of empty VMT to the average VMT increases as the percentage of DO/PU traffic increases. In the extreme case, when there is 100% DO/PU traffic, the empty VMT is approximately 50% of the average VMT.

Figure 10 also provides a visual plot of average CO_2 emissions versus different percentages of DO/PU traffic. CO_2 emissions first decrease as DO/PU traffic increases from 0% to 40%, which likely corresponds to the initial increase in the AV share of the vehicle market. When the DO/PU share of traffic by AVs surpasses 40%—and the parking share of traffic by conventional vehicles correspondingly decreases—overall VMT, congestion and, therefore, CO_2 emissions begin to increase. During this initial phase from 0–40%, since the percentage of conventional vehicles that require parking is high, the demand for parking is also high. Congestion and emissions primarily result from conventional vehicles cruising for parking and/or waiting for parking. The transition from conventional vehicles to AVs improves the shortage in parking resources: AVs that do not need parking spaces replace conventional vehicles that require on-street or off-street parking spaces. Vehicles in the network, hence, spend less time circulating on the road searching for parking spaces. Therefore, congestion and emissions are reduced. After some critical point (40% in this study), the situation becomes worse as the percentage of DO/PU traffic increases, if everything else is unchanged (e.g., total parking supply, road network, and total travel demand). In this late phase of AV adoption (> 40%), the benefits of AVs (or DO/PU vs. parking) in terms of reducing parking demand are off-set by the extra VMT and emissions created by AVs. AVs create empty VMT after dropping off passengers or when traveling from home to a PU location. This empty VMT inevitably creates additional congestion and emissions in the network.

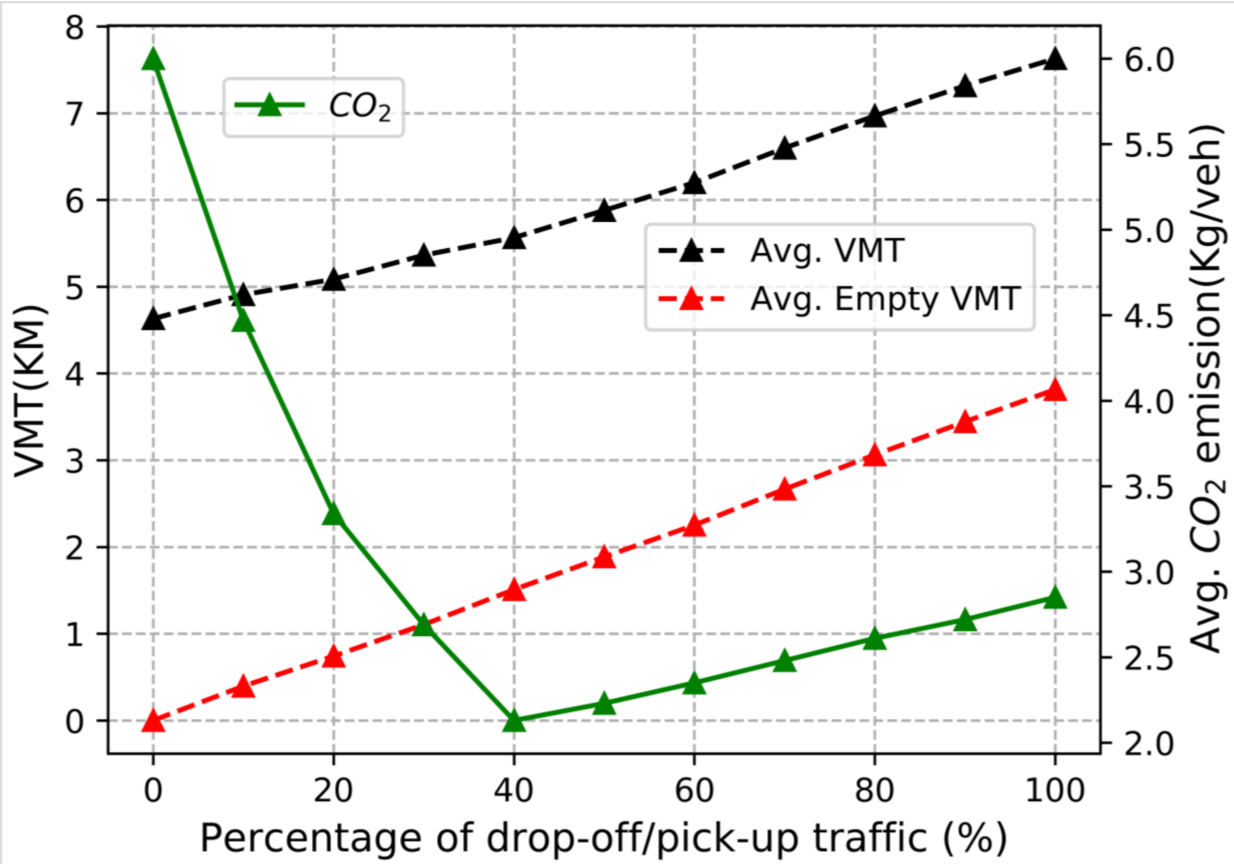


Figure 10. Scenario 1: Average (Avg.) daily VMT, empty VMT, and CO_2 emissions.

Scenario Set 2: Can the conversion of on-street parking spaces to DO/PU spaces address VMT and emissions impacts due to increased DO/PU demand?

In this scenario, the relationship between the percentage of dedicated DO/PU space and total VMT is not a simple linear correlation. When the percentage of the former increases from 0% to 35% (from the fitted curve in Figure 11), there is a decrease in average VMT and empty VMT. At this range, decreases in travel time and distance needed for vehicles to find DO/PU spaces drive the reduction in VMT. When the dedicated DO/PU percentage increases from 35% to 90%, average VMT and empty VMT increases. The rise in VMT after 35%, especially the huge spike at 90%, is primarily because more dedicated DO/PU locations lead to fewer on-street parking spaces, which increases the time and distance needed to locate an available parking space.

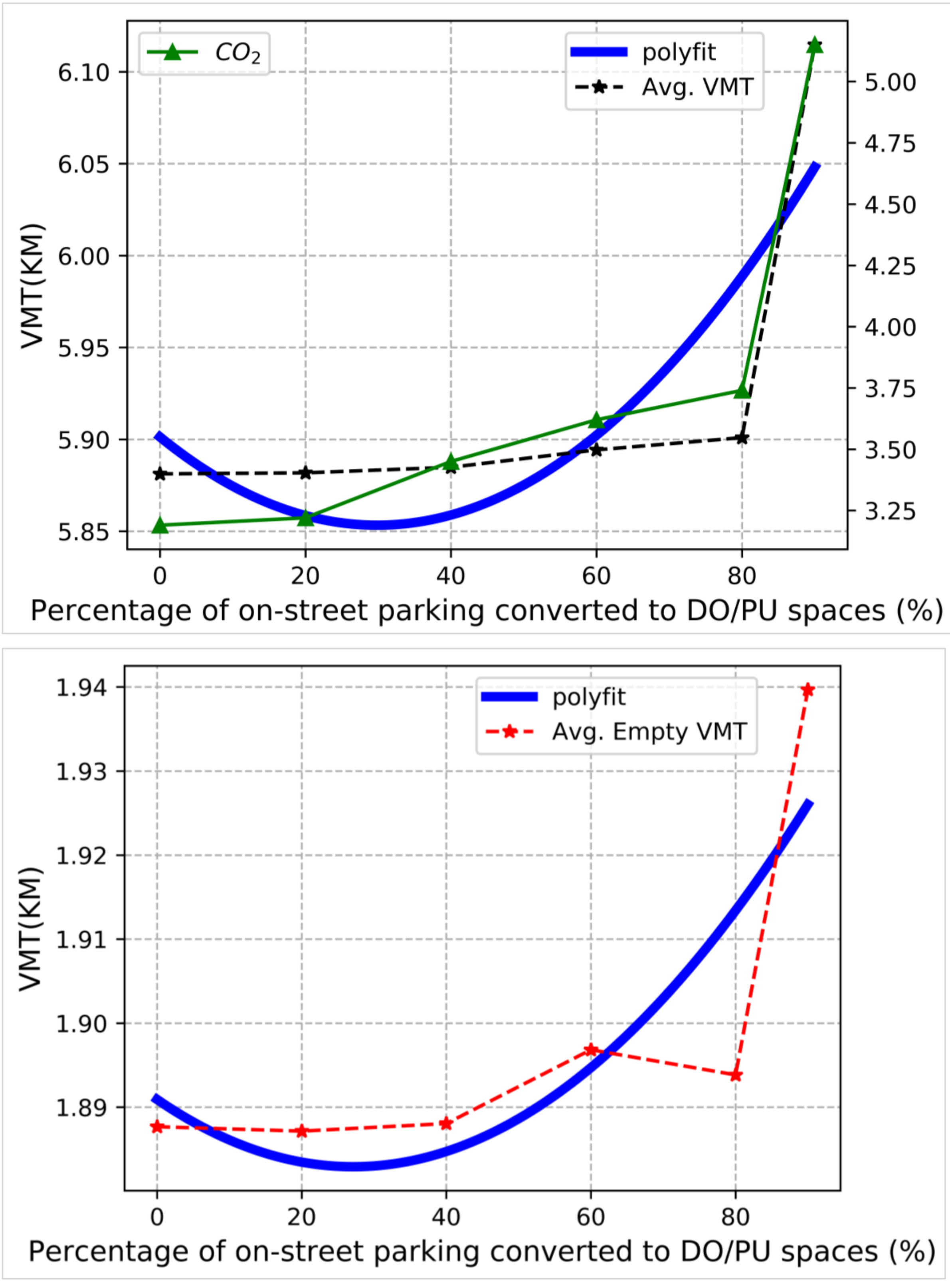
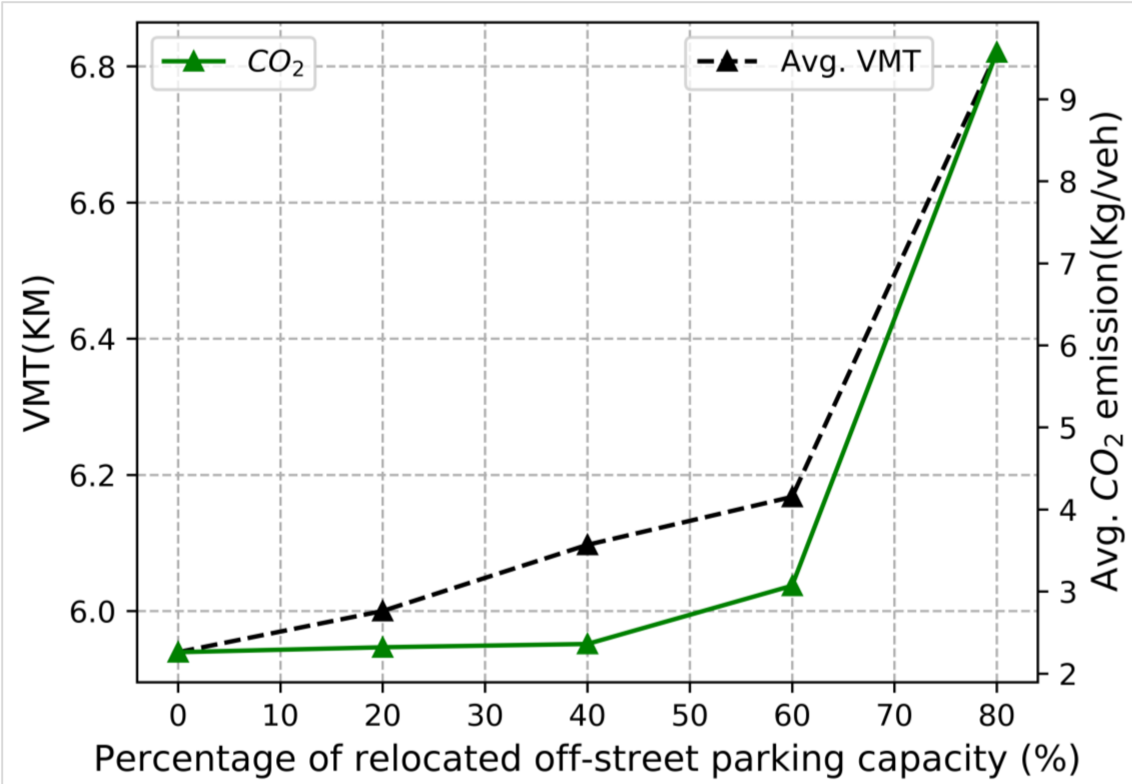


Figure 11. Scenario 2: (a) Average (Avg.) daily VMT and CO_2 emission. (b) Average daily empty VMT". ("polyfit" indicates polynomial curve fitting)

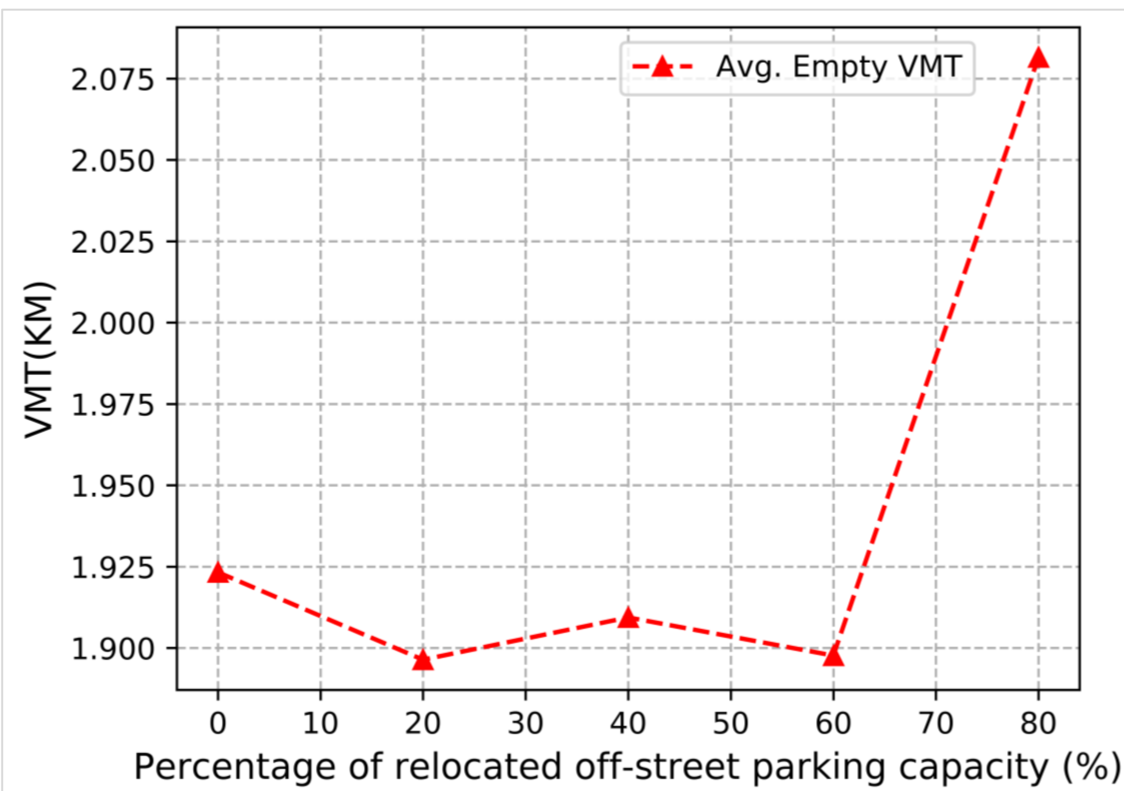
In Figure 11(a), we can see a positive relationship between average daily CO_2 emissions and the number of dedicated DO/PU spaces increase. As we convert more on-street parking spaces to dedicated DO/PU traffic spaces, more cruising for parking is required to find parking. Besides the extra cruising travel, DO/PU traffic creates traffic backups and congestion near the dedicated DO/PU locations. Therefore, more DO/PU dedicated space could further increase CO_2 emissions from vehicles that get stuck in traffic congestion.

Scenario Set 3: What are the VMT and emissions impacts of concentrating the supply of off-street parking in fewer parking facilities?

In this scenario, we concentrate the supply of off-street parking in fewer parking facilities. Figure 12 shows how average daily VMT, empty VMT, and CO_2 emissions respond to this reallocation of off-street parking. Overall, the metrics increase when off-street parking supply becomes more and more concentrated because vehicles need to travel longer distances to get to parking facilities. Also, the relatively concentrated off-street parking supply attracts vehicles to those parking facilities, which inevitably creates "hot spots" in the road network. These "hot spots" have dense traffic. Thus, such concentration of off-street parking will create severe traffic congestion near the parking facilities and contribute to more emissions (shown as the solid green line in Figure 12(a)).



(a)



(b)

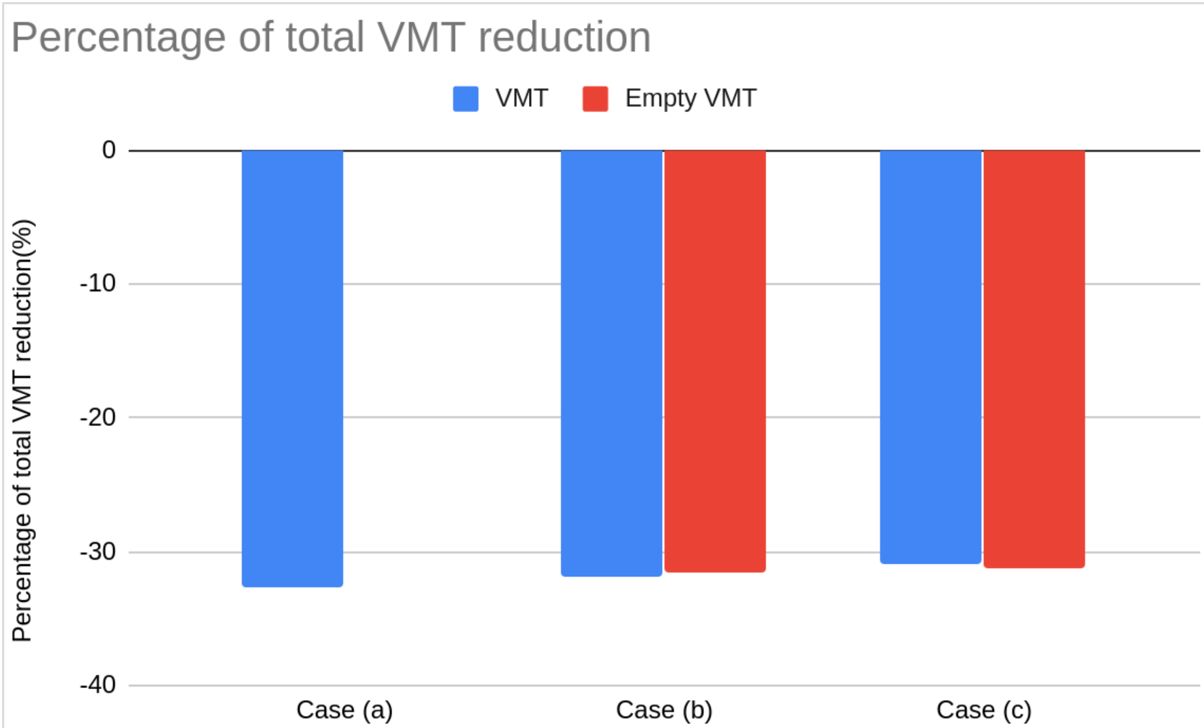
Figure 12. Scenario 3: (a) Average (Avg.) daily VMT and average CO_2 emission. (b) average daily empty VMT.

Scenario Set 4: How might plausible reductions in traffic demand from auto pricing policies impact the VMT and CO_2 emissions results for scenario sets 1 to 3, above?

In this scenario, we compare different test cases against base cases (see the descriptions in Table 1). The traffic demand in the test cases is reduced by 30% compared to the base cases. Figure 13 shows that in all cases (a–c), the total and average VMT and empty VMT all decrease with reduced traffic demand. In case (a), total VMT decreases by 33%. In cases (b) and (c), total VMT and empty VMT are each reduced by about 30%. The amount of reduced VMT approximately matches the amount of reduced traffic demand. Average VMT, on the other hand, does not change significantly across base cases and test cases because the percent reduction of total VMT and traffic demand is approximately the same.

CO_2 emissions also change in the test cases compared to the base cases (See Figure 14). In case (a), total CO_2 emissions are reduced by 72%, while average CO_2 emissions are reduced by 60%. In case (b), total CO_2 emissions are reduced by 32%, while the average CO_2 emissions are only reduced by 3%. In case (c), total CO_2 emissions are reduced by 31%, and the average CO_2 emissions are almost unchanged with a 1.7% reduction. Traffic in the base case (a) is heavily congested. The 30% reduction in traffic demand reduces total emission (less travel) and congestion. Vehicles spend less time in congestion and produce less average CO_2 emissions. However, traffic in the base case (b) and base case (c) is not as heavy as the base case (a). The effects of reducing traffic demand on traffic are not as significant. Therefore, the average emission reduction in these two cases is almost unchanged.

(a)



(b)

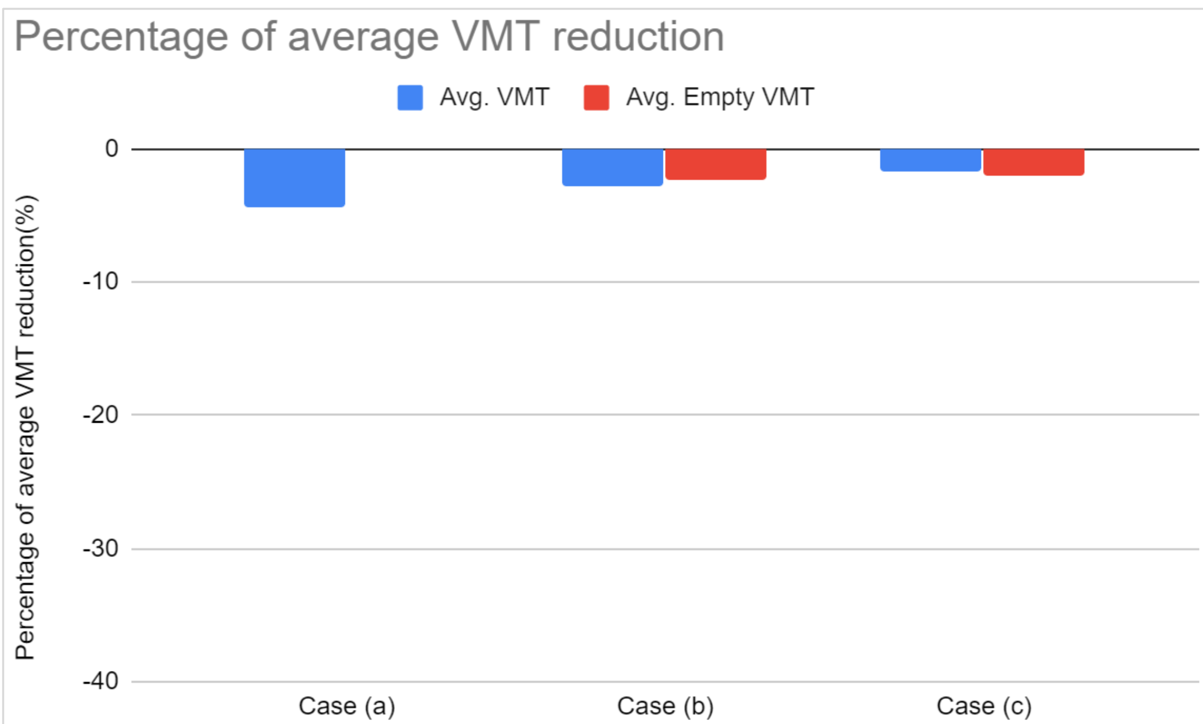


Figure 13. Scenario 4: Percentage change in (a) daily total and (b) average (Avg.) VMT and empty VMT.

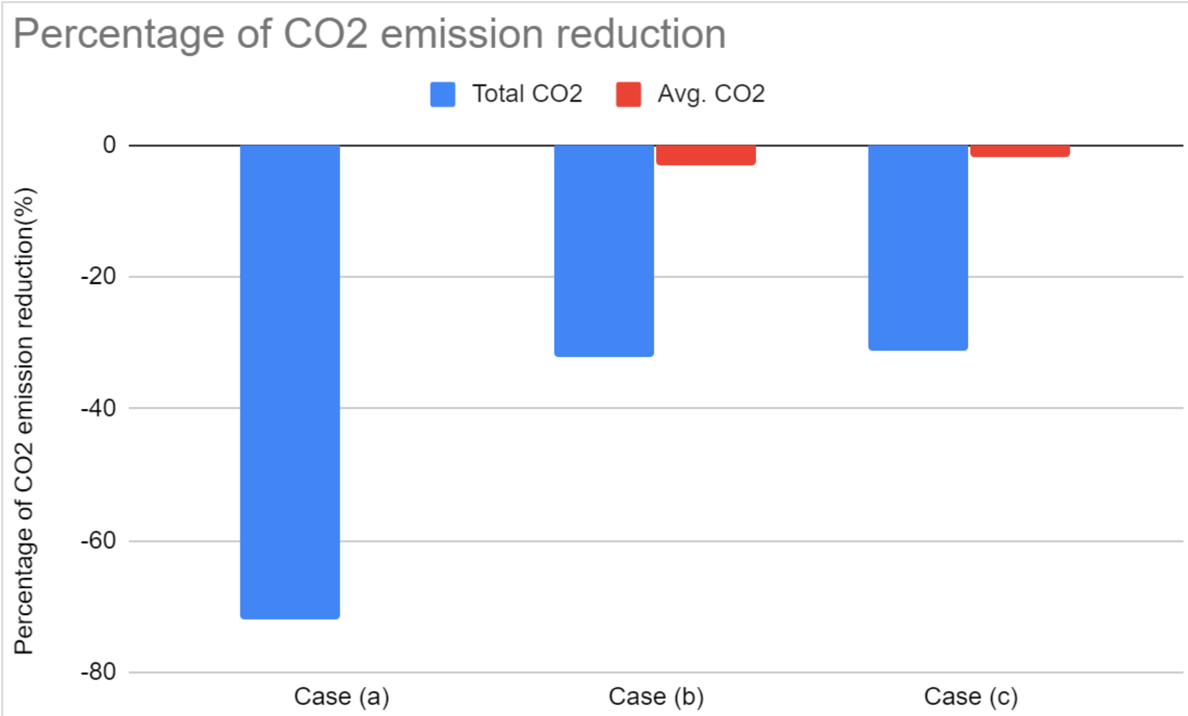


Figure 14. Scenario 4: Daily total CO_2 emission and average CO_2 emission.

Parking Revenue

The shift from paid parking in San 'Francisco's CBD to free DO /PU traffic could have a significant impact on parking revenues. In this section, we use the results from scenario set 1 to explore the effects on parking revenue and possible alternatives to recoup revenue losses.

In the scenario set 1, total parking revenue drops quickly as the percentage of DO/PU traffic rises, as shown in Figure 15(a). The trend is similar for on-street parking revenue and off-street parking revenue. Parking revenue is zero when all traffic ends with DOs and PUs.

To compensate for this potential parking revenue loss, we explore the possibility of implementing a DO/PU fee for any vehicle that uses the DO/PU zones. Figure 15(b) shows what would happen if we impose a $2.00 fee on every DO/PU vehicle within the study area. Note that we assume travelers will not change their travel behavior due to the new DO/PU fee. However, our analysis could over or underestimate revenue because the demand for trip ends in the study is based on existing parking costs in the CBD. We see that by collecting a $2.00 DO/PU fee the total ""parking revenue"" increases to approximately $36,000 in the 100% DO/PU case, which is only a quarter of that collected in the base case scenario (0% DO/PU). Figure 15(c) shows the DO/PU fees that would be required to obtain the same amount of revenues as the base case under a different percentage of DO/PU traffic. We estimated that the DO/PU fee needs to increase to approximately $10.00 per DO/PU trip in the extreme case.

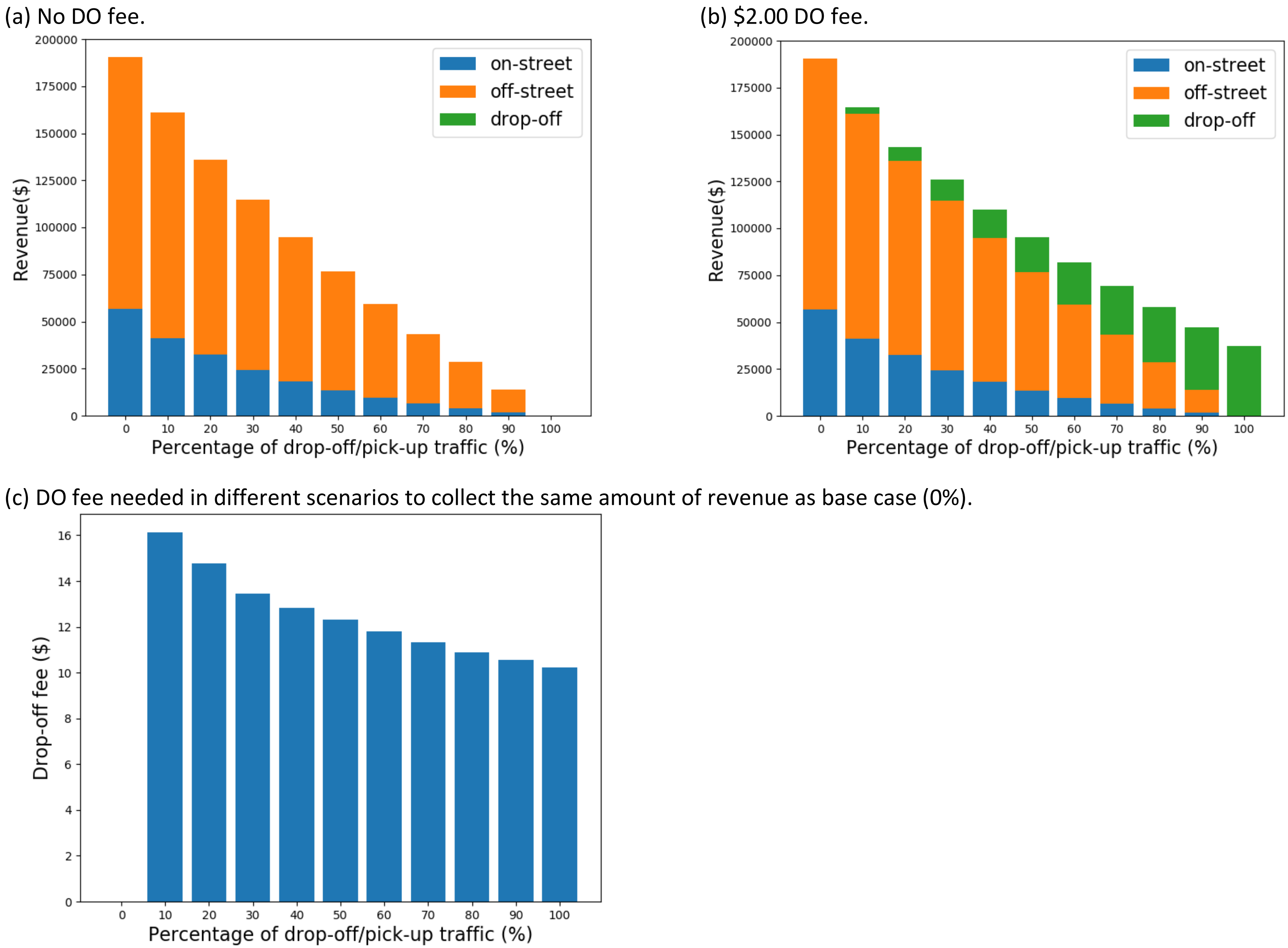


Figure 15. Parking revenue scenarios.

Conclusions

In this study, we used a microscopic road traffic model with local travel activity data to simulate vehicle travel in San 'Francisco's downtown central business district to explore traffic flow, VMT, and CO_2 effects of personal AV scenarios. In these scenarios, we vary (1) the demand for DO and PU travel versus parking, (2) the supply of on-street and off-street parking, and (3) the change in demand for parking and DO/PU travel due to a significant change in the cost of travel. The results explore answers to the following questions.

What are the impacts of increasing DO/PU demand relative to parking demand as AVs penetrate the vehicle market?

For the CBD study area, the shift from parking trips to DO/PU trips significantly reduces traffic delay because of avoided parking search travel and more efficient use of parking spaces. While a parked vehicle typically occupies a space for 2 hours, a DO/PU vehicle occupies a space for 20 seconds. At the CBD level, these traffic flow improvements are not off-set by increases in empty passenger VMT and vehicles exiting and entering the flow of traffic for DOs and PUs. However, on roads where the demand for parking and DO/PU spaces is relatively high, the opposite is true. Empty passenger VMT and increased vehicle movements do off-set the travel flow benefits from reduced parking search travel. Empty vehicle travel drive increases in VMT and CO_2 emissions.

We also examined changes in parking revenue for this scenario. We found a significant reduction in parking revenues, which could potentially be off-set by charging more than double the average hourly parking rate for a DO/PU event.

Can the conversion of on-street parking spaces to DO/PU spaces address impacts due to increased DO/PU demand?

An improved match between DO/PU demand and DO/PU spaces can reduce traffic congestion, VMT, and CO_2. However, the match must be specific to streets and time of day. An over-allocation of DO/PU spaces can increase parking search and empty vehicle travel, which can increase VMT and CO_2 emissions

It may be possible to redress some negative traffic flow impacts from increasing shares of DO/PU traffic. However, our results show that the conversion of parking spaces to DO/PU spaces must be street specific and dynamic over-time to adjust to changes in AV market shares. Such adjustments would require continuous, detailed roadway monitoring and planning, which may be a challenging task for many US cities.

What are the impacts of concentrating the supply of off-street parking in fewer parking facilities?

Our results show that increasing the concentration of off-street parking supply in fewer locations worsens CBD congestion. Increases in VMT are driven by empty vehicle travel and parking search travel, which, in addition to congestion, also increases CO_2 emissions. Strategies are needed to implement optimally relocate off-street parking capacity.

How might reduced traffic demand that may result from auto pricing policies impact the outcomes for scenarios that increase DO/PU demand, convert on-street parking to DO/PU spaces, and increase the concentration of off-street parking supply?

The 30% reduction in traffic demand in the CBD, which approximates the effects of a significant auto pricing policy, came close to eliminating congestion (as measured by vehicle speed and road occupancy). The change in VMT was relatively proportional to the change in traffic demand across all scenarios. However, the magnitude of congestion reduction CO_2 emissions depended on the size of the congestion problem in the base case for each scenario.

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Data Management

Products of Research

The simulation model in this study was developed and calibrated with the official San Francisco Bay Area Metropolitan Transportation 'Commission's Activity-Based Travel Demand Model (MTC-ABM). The geographic focus of this study is the central business district (CBD) in the City of San Francisco. We selected individual daily activity tours with at least one vehicle stop in San Francisco CBD from 5 am to 12 pm (an average weekday) from the SFBA-MATsim model.

The parking supply data was collected from SFpark website and processed into a SUMO-compatible format.

Data Format and Content

The dataset is presented in XML format which is the default format used by the simulation tool SUMO.

Data Access and Sharing

The dataset for the simulation model is available at https://doi.org/10.25338/B8DG7P

Reuse and Redistribution

The simulation models can be cited, provided that an attribution is given to this work and the dataset. The dataset should be cited as:

> Chai, Huajun; Rodier, Caroline (2020), AVs and Central Business District Parking, UC Davis, Dataset, https://doi.org/10.25338/B8DG7P