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Exploring the Economic, Environmental, and Travel Implications of Changes in Parking Choices due to Driverless Vehicles: An Agent Based Simulation Approach

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Abstract

Fully driverless automated vehicles (AVs) could considerably alter the proximity value of parking, due to an AV's ability to drop passengers off at their destination, search for cheaper parking, and return to pick up their occupants when needed. This study estimates the potential impact of privately-owned driverless vehicles on vehicle miles traveled (VMT), energy use, emissions, parking revenue, and daily parking cost savings in the city of Seattle, Washington from changes in parking decisions using an agent-based simulation model. Each AV is assumed to consider the cost to drive to each parking spot, the associated daily parking cost, and the parking availability at each location, and the AV ranks each choice in terms of economic cost. The simulation results indicate at the low penetration rates (5 to 25 percent AV penetration) AVs in downtown Seattle would travel an additional 3.5- 4.0 miles per day on average, and high penetration rates (50 to 100 percent AV penetration) would travel an additional 5.6-8.4 miles per day on average. The results also suggest that as AV penetration rates increase, parking lot revenues decrease significantly and could likely decline to the point where operating a lot is unsustainable economically, if no parking demand management policies are implemented. This could lead to changes in land use as the amount of parking needed in urban areas is reduced and cars move away from the downtown area for cheaper parking. This analysis provides an illustration of the first-order effects of AVs on the built environment and could help inform near and long- term policy and infrastructure decisions during the transition to automation.

Keywords: Driverless automated vehicles, Parking, Agent-based model

Introduction

Automated vehicle (AV) technologies are advancing rapidly and highly automated vehicles (HAVs) could be on streets and highways within the next decade. Many automakers are already marketing cars with some automated features such as adaptive cruise control and active lane keeping technologies (Newcomb and Colon 2017) and are progressively working to develop more highly automated and self-driving vehicles. Tesla Motors has stated they are equipping every new Model S sedan and Model X SUV with the necessary technology to eventually enable full self-driving capability, in exchange for about $8,000 (Stewart 2017). Ride-hailing company Uber has deployed a fleet of self-driving cars in Pittsburgh, Pennsylvania and several other cities, and has offered some customers the option of riding in these vehicles while Uber employees are monitoring behind the wheel (Brian 2016; Zurschmeide 2016). The United States Department of Transportation (USDOT) has released policy documents on AVs in 2016 and 2017, which provide guidelines to manufacturers and other stakeholders in the safe design, development, testing, and deployment of HAVs (NHTSA 2016; NHTSA 2017). This technology has the potential to greatly improve travel by reducing congestion, travel times, crashes, and potentially energy consumption, as well as enabling greater mobility for the disabled and elderly (Anderson et al. 2014; Harper et al. 2016b; a; Levin and Boyles 2015; Mersky and Samaras 2016; Wadud et al. 2016). There are six levels of automation, from "no automation" (level 0) to "full automation" (level 5), as defined by the Society of Automotive Engineers (SAE 2016). Level 5 AVs or fully driverless cars (and Level 4 AVs under certain conditions) could change parking patterns and decrease the need for proximity parking, which could lead to AVs parking further away from destination centers in more satellite locations (Anderson et al. 2014). The purpose of this study is to assess how changes in parking choices of privately owned AVs could impact vehicle miles traveled (VMT), parking revenues, daily parking cost savings, energy, and emissions. The authors construct an agent-based model to simulate privately owned AVs and parking choices in a case study using parking and travel survey data from the Puget Sound Regional Council for Seattle, Washington.

Automobile commuters in urban areas often use downtown parking garages and are charged relatively high daily parking prices. Street parking, while cheaper, is usually scarce in dense urban areas and requires drivers to spend time cruising in search of an available curb space, which creates congestion (Liu and Geroliminis 2016; Shoup 2006). In many cities, parking facilities tend to occupy considerable amounts of land that if not occupied for parking could be used for other purposes such as parks, office space, housing, retail, bicycle lanes, or other uses. Shoup (2005) estimates that about 5 to 8 percent of urban land is devoted to curb parking. Manville & Shoup (2005) estimated that the parking coverage -the ratio of parking area to land area- in Downtown Los Angeles and Houston are about 81 and 57 percent, respectively, if each parking space- curb parking, surface lots, and parking structures- were spread horizontally over a surface lot (Manville and Shoup 2005). Driverless cars could enable avoiding the garage charges, since these vehicles could self-park in cheaper, more distant parking locations (Anderson et al. 2014).

Fully automated (Level 5) vehicles could significantly alter the proximity value of parking, due to the ability of an AV to drop its passengers off at their destination, search for cheaper parking, and return to pick up their passengers when needed (referred to as driverless valet parking throughout this paper). As the automobile industry begins to transition towards partial vehicle automation, "limited" self-parking technologies are beginning to appear on the market in vehicles such as the Tesla X and BMW 7-series (D'Orazio 2016; Gorzelany 2016). In light of continued advancements in AV technologies, driverless valet parking systems could be on the market in the 2020s (Tilley 2016), although there remains uncertainty on when Level 5 technology will be ready for commercial implementation. Due to the large amount of land used by both curb parking and parking garages in dense urban areas, it is important for urban planners and transportation professionals to begin exploring the implications of driverless vehicles on travel patterns, parking revenues, as well as impacts from driverless trips (Stephens et al. 2016).

This paper investigates one aspect of the economic, energy, environmental, and travel implications of privately owned driverless vehicles by estimating changes in parking revenues and daily parking cost savings, greenhouse gas (GHG) emissions, and VMT from changes in parking choices in Seattle, Washington. These estimates are based on an agent-based model of privately owned driverless vehicles in Seattle with a constructed grid network of 0.1 km (.062 mile) street segments. The model uses parking data from the 2013 Puget Sound Regional Council (PSRC, 2013) Parking Inventory and simulates changes in parking decisions. Each AV selects a parking spot based on economic cost, which includes the operational cost of driving (maintenance, tires, fuel) to the parking spot, increased depreciation from the extra travel, as well as the associated daily parking cost. In addition, the AV also considers parking availability at each location. Within the model the authors vary influential parameters such as the cost of driving and AV penetration rates in a sensitivity analysis, to account for future uncertainty and to assess how parking demand management strategies could impact AV parking decisions. At the low penetration rates (5 to 25 percent AV penetration) AVs in Seattle would travel an additional 3.5- 4.0 miles per day on average, and high penetration rates (50 to 100 percent AV penetration) AVs in Seattle would travel an additional 5.6-8.4 miles per day on average. While, changes in energy use follow a similar trend, changes in parking occupancy rates mirror the AV penetration rate. At 5 and 25 percent AV penetration, parking lot occupancy decreases by 5 and 25 percent, respectively, and similar changes in occupancy rates are observed at higher AV penetration, if no parking demand management strategies or other policies are implemented. The estimates in this paper are meant to illustrate some potential impacts of AVs on the built environment and could help inform the near- and long-term policy, parking, and land use decisions of policymakers, planners, and other transportation professionals during the transition to automation.

Existing Literature

There are a few existing studies in the literature that addresses the implications of AVs on parking demand. Fagnant and Kockelman (2015) estimate approximately $250 in parking savings per new AV could be realized through reallocating parking from Central Business Districts (CBD) to less dense areas and car-sharing, and assume that AVs could save $1 in daily parking cost per work day. Zhang et al. (2015) investigated the impact of shared autonomous vehicles (SAVs) on urban parking demand using an agent-based model simulation, conducted on a 16 x 16 km (10 x 10 mile) grid-based hypothetical city. The main source of data for that study was the 2009 National Household Transportation Survey, which is used to assign departure and trip length for each trip generated in this model. Their study results indicate that SAVs could eliminate up to 90% of daily parking demand for clients who choose to adopt the system, at low penetration rates (Zhang et al. 2015). However, Zhang et al.'s study suggests that a reduction in parking demand comes at a cost, with significant increases in VMT due to empty vehicle cruising. Zakharenko (2016) developed a model to estimate the impacts of AVs on urban land use. Their study suggests that vehicle automation could cause cities to shrink by reducing the demand for parking land. Zakharenko assumes that there is a fixed amount of space for each resident and AVs return home for parking.

Fagnant and Kockleman (2014) explore the travel and environmental implications of SAVs using agent-based model scenarios and estimate that daily VMT could increase by about 11% from vehicles relocating to new zones when unoccupied.

This paper makes a contribution to the literature by using Seattle parking lot price and daily occupancy data to develop an agent-based model that simulates changes in parking choices in the Seattle region due to vehicle automation. This paper evaluates different scenarios than previous agent-based AV studies. While the existing literature focuses on SAVs, this is the first study the authors are aware of that quantifies the changes in travel demand, energy use, and parking revenues, when privately-owned vehicles (POVs) that currently park in downtown garages and lots are driverless and could self-park in cheaper more distant parking locations. While, the introduction of SAVs could potentially reduce vehicle ownership, initial research into current ride hailing models (e.g. Uber, Lyft), etc. have not encouraged users to get rid of their POVs (Clewlow et al. 2017). Clewlow et al. (2017) found that among users who don't use transit, there are no differences in vehicle ownership rates between ride hailing users and traditionally car-centric households. Users who use transit regularly may be more willing to give up their POVs, but those users are not the focus of this study. As stated earlier, Tesla Motors is already equipping their vehicles with the necessary technologies for full self-driving capability as well as Audi, which has introduced the first-to-market level 3 automated driving system with Traffic Jam Pilot on the Audi A8 and has plans to introduce a level 4 highway pilot feature by 2020 (Audi 2017). Whether or not individuals who traditionally drive are willing to get rid of their cars and switch to a car sharing model in a fully AV environment and how long this process could take is yet to be seen. While AVs could enter a market as mostly shared, it is also plausible that some, or many, AVs could be privately-owned. As a result, the authors think that focusing on POVs offers a new perspective and is a contribution to the current literature. In addition, it is still unclear how much parking occupancy and revenue is likely to be impacted due to this technology as well as the impacts of certain policies on AV parking decisions. This paper fills this gap through a simulation model, which is developed to estimate the potential impact of driverless valet systems on parking demand in Seattle's downtown area.

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Data

The data for this project were obtained from the Puget Sound Regional Council (PSRC) 2013 Parking Inventory, which is a complete inventory of all off- street parking located in the CBDs of the King, Kitsap, Pierce, and Snohomish Counties of Washington State, as well as the Seattle First Hill, Danny Regrade, and lower Queen Anne neighborhoods, and the University District. The regional inventory of off-street parking is conducted by PSRC. Each lot was surveyed during one morning (between the hours of 9:30 a.m. and 11:30 a.m.) and one afternoon period (between the hours of 1:30 p.m. and 3:30 p.m.). Each parking lot was coded to the 2010 census block-level in which it was located. The information collected includes the total number of parking lots and stalls and average daily occupancy rates, as well as average hourly and daily parking price. The 2013 PSRC Parking Inventory consists of 2,443 parking lots, including 816 lots that are located in Seattle. Of these 816 lots, approximately 376, or 46 percent, have daily parking costs recorded in the dataset, while the other lots may be free short-term parking reserved for customers of restaurants or convenience stores, are reserved for employee parking, or do not have recorded daily parking cost information. In other words, of the 376 lots that have a recorded daily parking cost information, about 290 lots, or 80 percent of the lots with recorded daily parking costs, are included in our dataset after cleaning data. The dataset was cleaned in order to remove inaccurate entries from the analysis where there were unrealistically high or low parking occupancy rates, as well as entries with missing occupancy, daily parking rate, and/or total stalls data. So, it is assumed that the 290 lots remaining in the authors' dataset represent about 80% of the public pay parking lots in Seattle, which appears to be a reasonable assumption given the PSRC inventory.

Since the authors are interested in exploring the changes in parking choice in dense urban areas due to driverless vehicles, the authors only consider daily parking lots located in downtown Seattle, while all other paid parking lots located outside of these areas were not considered. Entries with morning, afternoon, or average daily occupancy rates greater than 100% were disregarded from the dataset. Similarly, entries that report daily occupancy rates of 0%, were not considered. Entries with missing occupancy, daily parking rate, and/or total stalls data were truncated from the dataset. Some of the daily lot revenues and occupancy rates were unrealistically low for the purpose of this analysis. For example, there are several census blocks that have average daily parking occupancy rates below 5% and/or total daily parking revenues below $100. Entries with estimated total daily lot revenues below $250 or per lot occupancy rates below 10% were removed from the dataset. Total daily lot revenues are estimated by multiplying average number of stalls occupied throughout the course of a day by the daily parking price. The City of Seattle estimates that it costs about $190 a day in $2002 to operate a staffed surface lot facility with 100 stalls in the city of Seattle when considering operating costs such as labor, accounting, and utility costs (City of Seattle 2002). Because the parking inventory data used for this paper is from the year 2013, the Consumer Price Index (CPI) was used to convert all daily operating costs to 2013 dollars, which is approximately $250, which is why this value was chosen as the authors' truncation point (Bureau of Labor Statistics 2017). After filtering, there are about 290 parking lots left in the authors' dataset, which represents about 80% of the daily parking lots in Seattle.

Table 1 lists descriptive statistics for surveyed off-street parking in downtown Seattle at the census block-level. The authors have included the descriptive statistics to provide the reader with an overview state of the parking lots in downtown Seattle, which were used as an input in this simulation. The descriptive statistics provides information on lot occupancy rates, daily revenue generated, and the price individuals are currently paying to park in the downtown area. There are about 47,000 total daily parking stalls in the sample. The average daily rate to park in an off-street parking facility in downtown Seattle is about $19. On average, each census block in the downtown area that has a daily parking lot, generates about $3,500 in total daily parking revenue and the garages in these census blocks have an average occupancy rate of about 68% throughout the day Each census block generates about $12.70 in daily revenue per stall and in most cases contains about 1 or 2 lots with each lot having about 250 total parking spaces. Total daily parking garage revenue for downtown Seattle is about $666,000; this would equal about $170 million in total annual parking revenue from drivers parking in downtown Seattle on weekdays.

Table 1. Summary Statistics of Puget Sound Regional Council Parking Inventory Census Block-Level Attributes

Statistic	Mean	SD	Min	Max
Census Block Records (n=192)				
Daily Occupancy Rate	68%	16%	13%	100%
Total Daily Revenue ($2013)	$3,500	$4,121	$260	$21,000
Daily Price	$19	$7	$7	$42.00
Daily Revenue Per Stall	$13	$6	$1.5	$35
Total Stalls	250	260	20	1,500
No. of Lots[1]	1.50	0.80	1	5

Note: SD=standard deviation; min=minimum; max=maximum

[1]Descriptive Statistics for paid surface lots and parking garages with daily parking at the census block-level.

Although, some employers currently subsidize employee parking downtown, it is possible in a fully automated vehicle environment for employers to instead reimburse travel costs for parking. The data does not specify what percentage of cars in each individual garage are there for shopping, entertainment, leisure, or are commuters. In addition, the level of subsidy varies from employer to employer and it is not certain as to how employers will handle parking subsidies in a fully AV environment where distant parking is now possible. As a result, the authors assume that all drivers parked in the downtown garages and lots currently pay the total daily parking cost and that each AV will make a decision based on this cost.

Methods

To simulate how driverless valet parking could change parking choices the authors first identify those areas in Seattle with free or unpaid parking. Using parking information from the city of Seattle, the authors model unrestricted parking in ArcGIS by creating sample zones throughout Seattle where vehicles can park during the day with no parking restrictions. The authors then develop an agent-based model, assuming a gridded network, where agent AVs search for cheaper parking and make decisions based on parking availability as well as cost. The simulation ignores the actual roadway geometry and assumes a rectangular grid throughout the entire study area.

Estimation of Unrestricted Parking Spaces in Seattle

Seattle has free, available parking spaces that outnumber paid garage spaces. According to the 2013 PSRC Parking Inventory, there are about 30,000 cars parked in downtown Seattle throughout a typical day. Seattle is estimated to have about 500,000 curb parking spots with about 470,000 and 12,000 total unrestricted and paid street parking spots, respectively, while the remaining parking spots are restricted parking spots (e.g. residential parking zones) that require a permit to park. The authors developed a sample set of unrestricted street parking zones close to downtown by identifying those portions of Seattle with abundant amounts of unrestricted parking available, using data from the Seattle Department of Transportation (SDOT), as shown in Fig. 1. SDOT has street block face data available that contains parking information for each block face in the city of Seattle. This dataset contains estimates on the number of unrestricted, paid, and residential parking spots as well as their locations. Seattle defines unrestricted parking as a type of on-street parking where there are no signs restricting the time or type of vehicle that can park there (Seattle Department of Transportation 2016a). The City of Seattle estimates the total number of parking spots on each block face by assuming that 30% of the road segment is occupied by driveways and alleys and that the size of a standard parking spot along curb is 5.3 meters (17.5 ft) (Seattle Department of Transportation 2016b), and the authors used these assumptions in estimating the number of unrestricted parking spaces in the sample zones. The authors sample unrestricted parking zones consist of about 67,000 total parking spaces, and the authors assumed 50% (or 33,000) of these parking spaces to be available on a typical day. These zones represent about 14% of the total unrestricted curb parking in the city.

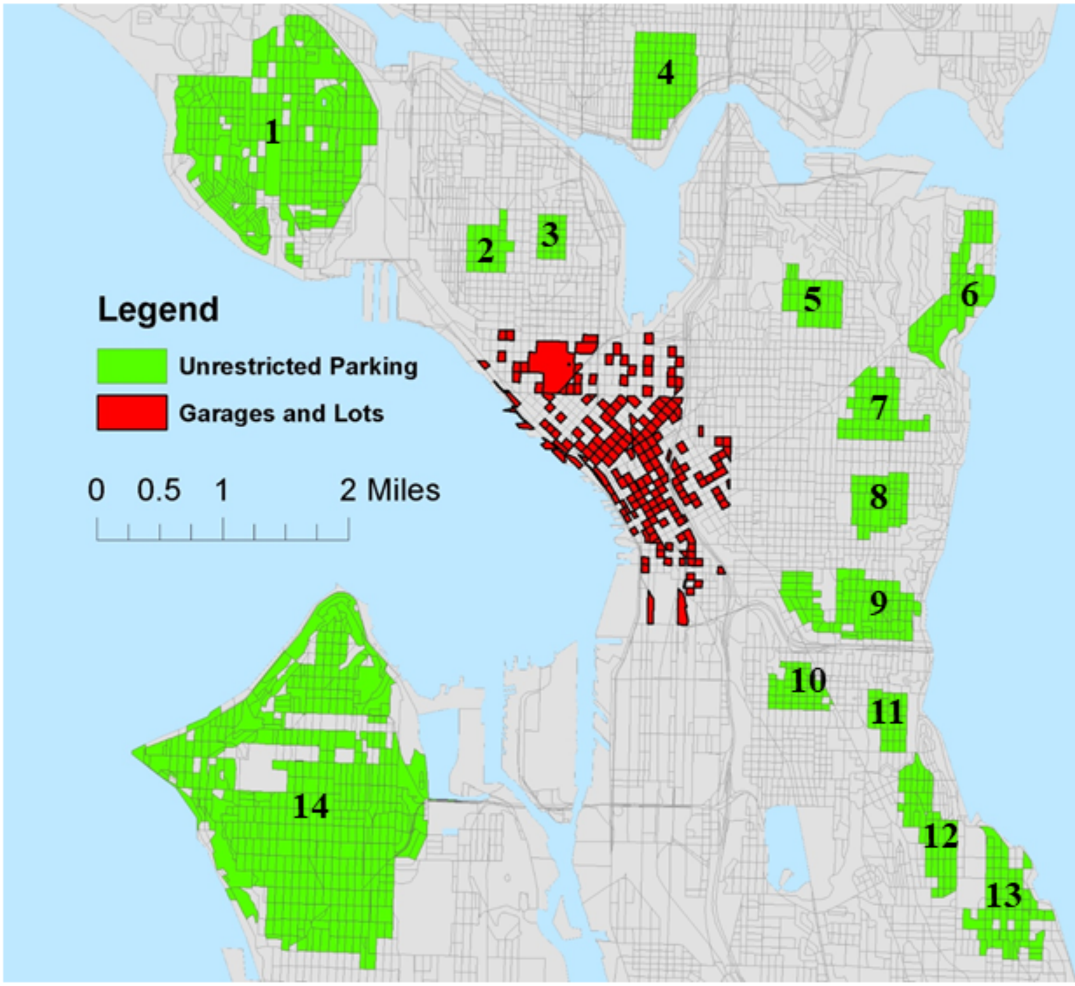

Fig. 1. Seattle's sample unrestricted parking zones (numbered 1–14) and downtown daily parking lots and garages. Each unrestricted parking zone is designated a number that starts from the top left corner of the figure and increases clockwise.

The total number of unrestricted spots on each block are estimated in the dataset by subtracting the number of time limit, residential parking, and no parking spaces from the total number of spaces. Although, the city of Seattle estimates the total number of unrestricted parking spots on each block, most of these parking spots are located in residential areas and could be occupied by cars during course of the day. The number of available parking spaces (Table 2 column 7) is the product of the total number of unrestricted parking spaces in zone and the percentage of occupied parking and is expressed in Eq. (1):

$$AS = US \times (1 - P_{OS}) \tag{1}$$

Where AS is the total number of available unrestricted parking spaces in each zone, US is the total number of unrestricted parking spaces and P_{OS} is the percentage of parking spots assumed to be already occupied by cars; for each zone the authors assume 50%. The number of parking spots in each sample unrestricted parking zone (UPZ) is shown in Table 2.

Table 2. Unrestricted Parking Information by Sample Zone

Sample Unrestricted Parking Zone # (UPZ)	Neighborhood	Area (acres)	Total Unrestricted Parking Curb Miles	Total No. of Unrestricted Parking Spots	No. of Available Parking Spots[a]	Parking Density[b]
1	Magnolia	1,200	88	16,000	8,000	14
2	Queen Anne	80	6	1,100	500	13
3	Queen Anne	50	5	900	400	17
4	Wallingford	230	18	2,900	1,500	13
5	Capitol Hill	100	9	1,600	800	14
6	Central Area, Capitol Hill	210	14	2,600	1,300	13
7	Central Area	150	13	2,400	1,200	15
8	Central Area	130	11	1,900	1,000	15
9	Central Area	260	21	3,800	1,900	15
10	Beacon Hill	90	8	1,500	700	16

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11	Rainer Valley	80	7	1,300	700	16
12	Rainer Valley	170	14	2,700	1,400	16
13	Seward Park	200	17	3,200	1,600	14
14	West Seattle	2,100	130	24,000	12,000	11
Total	na	5,100	360	66,000	33,000	na

Note: numbers may not sum exactly due to rounding.

[a]50% of Total Unrestricted Parking spots assumed to be occupied by cars in each zone.

[b] Total No. of unrestricted parking spots/acres of land

Model Parameters and Specifications

The agents in this model are empty AVs starting in downtown Seattle in search of cheaper parking. AV penetration rates vary between each scenario, from a single driverless vehicle making parking choices in the initial scenario to all cars being driverless in the highest AV penetration scenario. AVs are deployed randomly from each downtown parking lot and the simulation continues to run until all AVs have selected a parking spot. The model assumes that each driver's final destination is within comfortable walking distance, 0.40 km (1/4 mile), of their parking location. As a result, the authors use the parking lot where the driver is initially parked as a proxy for the AVs starting location. The authors believe that starting the AVs at the downtown parking location is within the bounds of existing uncertainty for this model. Each AV's objective is to minimize total daily parking costs, which includes the roundtrip operational cost of driving to the parking spot, increased depreciation from extra travel, as well as the associated daily parking cost, and are constrained by the parking availability at each location. AVs estimate the distance from their starting location to each available parking spot using the sum of the absolute value of the difference between the x and y coordinates or the Manhattan distance (i.e. distance between two points measured along axes at right angles) (Black 2006).

To provide an initial estimate and baseline for comparison, this model uses conventionally-fueled, privately-owned light duty vehicles, assumes vehicle ownership remains constant, and that drivers do not shift to shared mobility. The operational per mile cost of driving a medium-sized sedan, which includes maintenance, tires, depreciation, and fuel, as well as increased depreciation costs from extra travel are assumed to be about 25 cents per mile and obtained from the 2013 AAA Your Cost of Driving report (AAA 2013). These decision variables are used in the optimization:

$Dist_{ij}$
$= Manhattan\ Distance\ from\ node\ i\ (starting\ location\ )\ to\ node\ j\ (parking\ destination)$
$Drive =$ per − mile operational cost of driving a medium sized sedan
$Daily_j =$ is the cost to park at node j

The objective function and constraints for the agents in this model are expressed in Eq. (2) and Eq. (3), respectively:

$$\min \qquad TC_{ij} = \min\left[2 \times (Dist_{ij} \times Drive) + Daily_j\right], \quad \forall\, i, \forall j \tag{2}$$

$$subject\ to \qquad Avail_j \geq 1 \quad for\ j = 1, \ldots, m \tag{3}$$

where, $\min TC_{ij}$, the minimum total cost from your starting point (denoted as i) to your parking destination (denoted as j), is the sum of the round-trip operational cost of driving from your starting point to your parking destination and the daily cost to park at your parking destination. Your decision variables are as follows: $Dist_{ij}$ is the Manhattan distance from node i to node j, $Drive$ is the per-mile operational cost of driving a medium sized sedan in 2013, $Daily_j$ is the cost to park at node j for the duration of the day, and $Avail_j$ is the parking availability at node j, which is meant to ensure that there is at least one parking spot available at the desired parking spot.

This paper assumes a connected, automated environment where vehicles can communicate with each other, as well as with infrastructure and city networks, which is one proposed system architecture for driverless vehicles. In this system, the location and status of all current parking spaces is known, and demand can be assigned and reserved by a parking system operator for all vehicles communicating with the system once the vehicle begins a journey. Even non-autonomous but connected vehicles could participate in this system. Any deviations where a non-connected car occupied a reserved space, the next closest space would automatically be found and the driverless car routed to it by the system operator. Each AV in this model is hence assumed to be fully autonomous and connected and have information of the locations and parking occupancy of each parking garage and UPZ in Seattle. Thus, AVs would not spend time cruising or searching for available parking. The implications of varying this assumption are discussed in the Sensitivity Section.

Whenever an AV chooses to move to a parking spot, the authors estimate the roundtrip distance traveled by the empty AV, the loss in downtown parking revenue, energy used, GHGs emissions emitted, and the change in parking occupancy. These increases are summed and used to determine how changes in parking choices could change light-duty VMT and emissions and parking revenue in the city of Seattle. By the end of the simulation, parking occupancy will be estimated for each census block that contains a daily parking garage in downtown Seattle. The total GHG emissions generated from extra travel for parking is expressed in Eq. (4):

$$E = \sum_{i}^{n} [(CO_2/gal) \times (gal/mile) \times VMT_i] \tag{4}$$

where E is the total GHG emissions emitted from empty AVs traveling longer distances for more economical parking, CO_2/gal is the amount of direct CO_2 in a gallon of gasoline (8,890 g), $gal/mile$ is the average fuel consumption for passenger cars in the city of Seattle for the year 2014 ($1\ gal/23\ miles$), and VMT_i is the additional roundtrip travel miles from empty vehicle i, (NHTSA 2010; Seattle Office of Sustainability and Environment 2016). As the fleet of driverless vehicles are likely to have higher fuel economy and/or increasingly be electrified vehicles in the future, the per mile results represent an upper bound. Using 127.1 MJ/gallon (EIA 2016), the authors also estimate energy use from the additional travel.

The simulation model is programmed in Python with the data visualization done in ArcGIS. In this model, AV penetration rates determine the amount of AVs in search of cheaper parking, which the authors assume to be uniformly distributed across the parking lots and garages in downtown Seattle. For example, an AV penetration rate of 10% means that 10% of the cars in each downtown parking lot are now assumed to be driverless and can now search for parking elsewhere in the city. The AV considers and ranks all available parking choices in the parking sample, both free and paid, and chooses the parking spot that minimizes cost to the user and has at least one available parking spot. For the unrestricted parking zones the authors use the centroid coordinate of the most centrally located census block as a reference point from which the authors estimate distance, emissions, and associated travel costs for the entire zone. The centroid of each census block included in this analysis is assigned to the node on the grid closest in proximity. The aim of this study is not to create a microsimulation model that takes into account traffic flow and route choices, which could be incorporated into future modeling efforts to highlight potential congestion impacts on specific routes. Since AVs are minimizing costs rather than time, the sensitivity analysis captures the economic implications of the more detailed components of the travel process.

Agent Parking Selection

The agents in this model use a greedy parking assignment, where the AV selects and reserves the most economical parking spot closest to its starting location (i.e. the downtown parking lot where the car was originally parked) through the parking system operator. As a result, some users will be able to obtain parking spots close to their destinations while others will have to travel to parking spots far from their starting locations. The agents in this model do not cruise for parking and will only travel to an UPZ or lot if there is an available parking space. The model does not allow for more than one AV to compete for the same parking spot. Instead, once one AV decides to travel to and reserves a parking space, this space is no longer available to the other AVs. For example, if 5 AVs are deployed from a parking lot and there is only one available spot at the ideal parking location, then only one AV will travel to the ideal parking spot while the other 4 AVs will travel to the next most economical parking spot with an available space. In other words, the model does not allow for the number of AVs traveling to a parking location to be greater than the parking availability at this location.

This analysis is only focused on simulating changes in parking decisions for AVs, and as a result all non-AVs in this model are assumed to start and end the day at its original parking location. The base case assumption for this model is that 50% of the parking spots in the unrestricted parking zones (UPZ) are occupied by cars before the simulation begins and this assumption holds true for all penetration rates. Non-AVs do not have the ability to drop its passenger off, search for cheaper parking, and pick its passengers up when needed, and are not agents in this model. As free parking zones fill up, there could be VMT from non-AVs cruising for parking in that zone. These impacts are not modeled in this simulation.

Results

The following sections describe the results from which the authors estimate changes in the impacts mentioned above, discuss the results, and provide guidance for other regions interested in planning for automated vehicle futures. These scenarios explore how driverless cars can influence parking choices, parking revenues, and travel demand impacts from empty vehicle trips.

Single Driverless Vehicle in Downtown Seattle

The authors start by placing a single driverless vehicle in downtown Seattle and ranking the potential parking choices in the city, which allows for an understanding of the decision process that an AV agent uses when selecting a parking location as well as the potential cost savings from driverless valet parking systems. In this scenario, one non-autonomous vehicle in a downtown Seattle area parking lot is replaced by a driverless vehicle that is now in search of cheaper parking.

In order to visually demonstrate the parking decisions made by AVs in this model, the authors position a single driverless vehicle in the largest census block (in terms of area) in downtown Seattle with at least one public daily parking garage. This census tract and block is located in north downtown Seattle and contains 3 daily parking lots with approximately 100 stalls each and average daily parking prices and occupancies of \$12.70 and 36%, respectively. The most economical parking spot from this starting location is a free parking space located about 1 mile away and if parking is available could save each driver about \$12 in daily parking costs, when only considering the round trip operational cost of driving. If parking is not available at the parking spot with the lowest cost, the AV then considers the parking option with the second lowest associated cost and so forth until an available parking spot is found. The second and third most economical parking spots are 1.5 and 2.5 miles away, respectively, from this starting point and parking at one of these parking zones could reduce daily parking costs by about \$11. Fig. 2 (shown below) displays the top three most economical parking locations in Seattle respective to the AV's starting location in this example.

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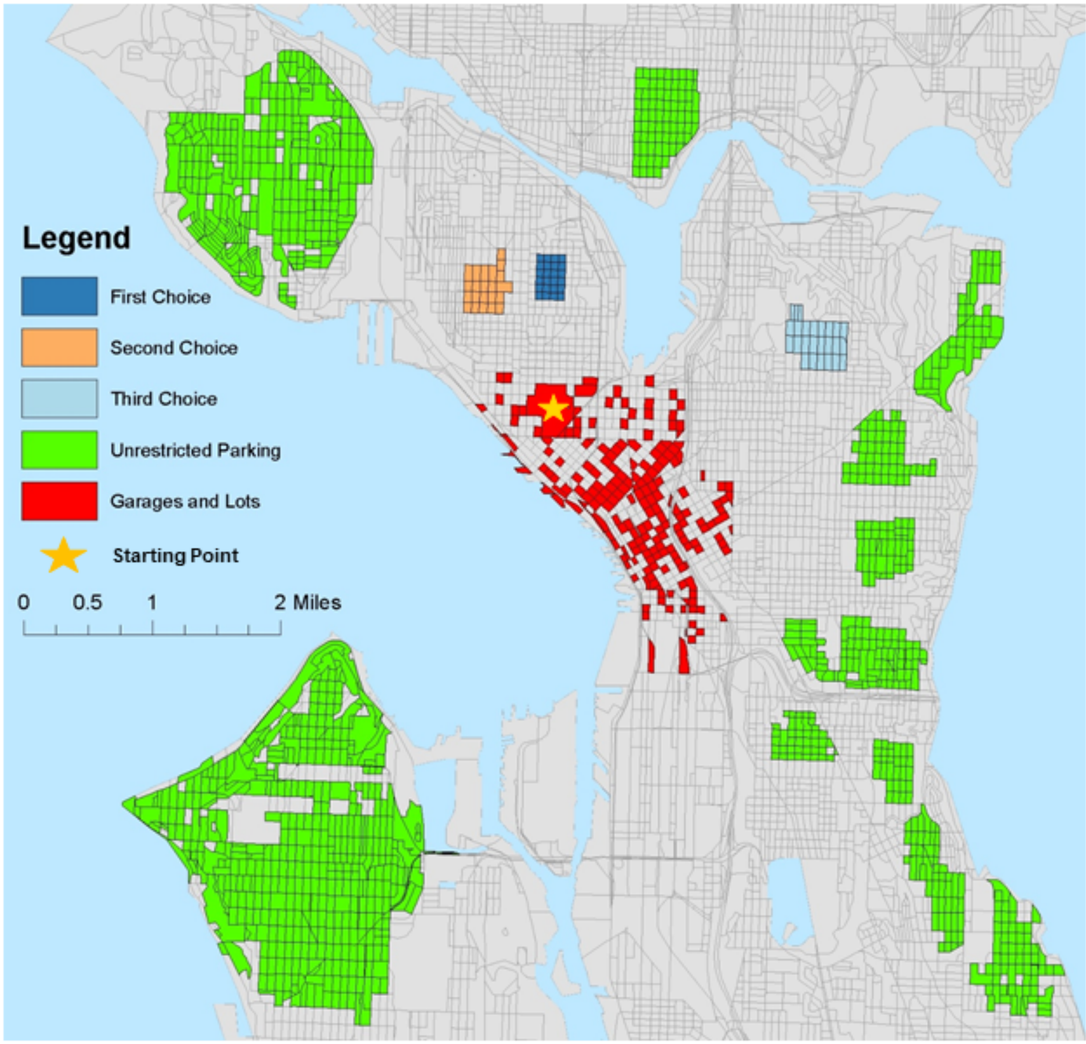

Fig. 2. Top three parking choices to minimize daily costs for a single driverless vehicle starting in downtown Seattle.

AV parking choices are shown below in Table 3 and ranked in ascending order in terms of economic cost. Free parking could range anywhere between 1 and 7 miles away from the starting location and could save the vehicle owner considerable amounts of money, but each individual vehicle would increase their daily travel demand considerably, relative to the existing average vehicle, especially as AVs begin to travel to those UPZs father away from downtown. As expected, the farther away the AV moves from downtown area, the greater the number of free parking spaces are available. There are about 1,100 more parking spots in the fifth ranked parking choice, which is about 3 miles away when compared to top ranked parking choice, which is only about a mile away. While the fifth most economical parking is not close to the AV's starting location, parking here would only cost the vehicle about $1.60 in daily parking costs. Even if the AV decided to travel to the farthest UPZ for an available parking space, which is located about 6 miles away (one-way) from the starting location, this round-trip would only cost the vehicle about $3.00 in daily parking costs. Although, AVs have the ability to park in cheaper, more distant parking locations, this added VMT could generate emissions and energy use that would otherwise not occur. For example, if this AV traveling to its first or third ranked parking choice, would generate about 0.8 kg or 1.9 kg of CO_2, respectively. While, this added emissions to the Seattle region may have insignificant impacts on total GHG at low AV penetration rates, this could begin to cause environmental concerns at higher penetration rates, which will be explored further in the next section. The authors do not explore the impacts of conventional air pollutants from tailpipes in this study, which requires a higher resolution localized analysis in future work.

Table 3. Ranked Parking Choices for a Single Driverless Vehicle Starting in Downtown Seattle[a]

Parking Choice Rank[b]	No. of Available Parking Spots	Round-Trip Distance (miles)	Round-Trip Travel and Parking Cost	Round-Trip Emissions (kg CO_2)	Round-Trip Energy Use (MJ)	Daily Cost Savings
1	400	2.1	$0.55	0.8	12	$12
2	500	3.1	$0.80	1.2	17	$12
3	800	5	$1.30	1.9	28	$11
4	1,200	5.7	$1.50	2.2	32	$11
5	1,500	6	$1.60	2.3	33	$11
n	…	…	…	…		…
206	200	1.4	$42	0.6	15	($30)

Note: Results will vary by starting location of driverless vehicle.

Note: It is assumed that driverless vehicle will drop-of and pick passenger up at starting location.

[a]Driverless vehicle was positioned to start at Tract 7001 and Block 2001.

[b]Parking choices are ranked in ascending order based on economic costs.

Increasing Market Penetration Rate of Fully Automated Vehicles in Downtown Seattle

In order to assess the travel, environmental, and economic implications of driverless vehicles the authors increase the market penetration rate of AVs in the downtown Seattle area in search of parking. This captures market penetration rates from the point in time where AVs have only been partially adopted by those in higher income households to a point in time where AVs transition from high-income early adopters to total market penetration.

On-road GHGs comprise about 40% of Seattle's total emissions. In 2014, the annual emissions from road transportation sector totaled about 2.34 million metric tons CO_2-e with passenger cars comprising about 75% or 1.72 million metric tons CO_2-e of all surface transportation emissions in the city (Seattle Office of Sustainability and Environment 2016). This base GHG estimate was obtained from the 2014 Seattle Community Greenhouse Gas Emissions Inventory, conducted by Seattle's Office of Sustainability and Environment (Seattle Office of Sustainability and Environment 2016). In order to estimate the total annual average weekday VMT for the city of Seattle the authors use the trip dataset from the 2014 PSRC Household Activity Travel Survey. From this survey the authors estimate that light-duty vehicles (cars and light-trucks) travel about 10.3 million miles daily in the city of Seattle. The base VMT in this study was estimated using a similar process to that found in the 2014 Seattle Community Greenhouse Gas Emissions Inventory for estimating average weekday VMT from all vehicles traveling entirely in, starting in, or ending in Seattle. This study as well as the inventory employs a method that counts emissions from all trips that occur entirely within Seattle, half of trips that either begin or end in the city, and no trips that both begin and end outside the city (even if they pass through the city), known as an origin-destination pair approach. This is an increasingly common way of counting GHG emissions in community-scale inventories, and was recommended in the International Council for Local Environmental Initiatives' (ICLEI) U.S. Community Protocol (ICLEI 2013). According to the 2014 Household Activity Travel Survey there are about 940 thousand vehicles that are traveling in, out, and around Seattle during the course of the day, making the average daily VMT per vehicle in Seattle about 11 miles.

VMT and energy use increase as the AV penetration rate goes up, but the authors do not see significant total increases due to the relatively low number of cars parking in the daily parking lots and garages, when compared to the total number cars making trips in and out of Seattle during the day. Under static parking pricing, parking lot revenues decline to the point where owning a parking lot or garage would no longer be feasible from an economic perspective. At low penetration rates AVs are usually able to obtain their top ranked parking choice, which in most cases is the free parking zone closest to their starting location and as a result the increase in VMT and emissions per AV at a 5% penetration rate is the lowest. At this penetration rate each vehicle would increase their daily travel by about 3.6 miles and due to the low penetration rate would have negligible impacts on light-duty VMT and emissions in the Seattle region. At a 75% penetration rate each AV travels about twice as much on average as they did at the 5% penetration rate. This indicates that AVs would rather travel longer distances for free parking than to park close by in a paid parking garage or lot due to savings in cost. If 75% of all cars parked in the downtown Seattle region had the ability to park in cheaper, more distant parking locations, this would only increase daily light-duty VMT and emissions in Seattle by 1.4% and 1.3%, respectively. Even at a 100% penetration rate daily light-duty VMT and emissions would only increase by about 2.5% and 2.1%, respectively, with each AV traveling about 8 additional miles each day. A 2.5% increase in VMT, while not a large increase in terms of daily city VMT, could have implications on congestion in the city; this is due to the fact that increases in congestion are nonlinear and the marginal increases in congestion are likely to exceed the marginal increases in VMT. In this simulation, parking lot revenue loss is equivalent to the AV penetration rate since it is currently cheaper to travel to park in an unrestricted parking zone than to park in a garage downtown for the day. The least expensive daily parking spot in downtown Seattle cost about $7, which is still more expensive than a car traveling the length of the grid (6.5 miles) to obtain a free parking spot. On average, each AV saves users about $18 in daily parking costs from choosing more distant, cheaper parking. Estimates of changes in VMT and emissions in the city of Seattle is shown below in Table 4.

Table 4. Changes in Vehicle Miles Traveled, Emissions, and Energy Use from Changes in Parking Choices in the City of Seattle

AV Penetration Rate	Number of AVs[a]	Total Increase in Daily VMT	% Increase in Total Daily Seattle VMT	Total Increase in Daily Emissions (metric tons CO_2)	Total Increase in Daily Energy Use (GJ)	% Increase in Total Daily Seattle Emissions and Energy Use[b]
5%	1,400	5,500	0.05%	2	30	0.05%
25%	7,400	32,000	0.30%	10	180	0.25%
50%	15,000	90,000	0.90%	30	500	0.80%
75%	22,000	170,000	1.70%	60	940	1.40%
100%	30,000	260,000	2.50%	90	1,400	2.10%

Note: AV is automated vehicle

[a]Column represents the number of automated vehicles now in search of cheaper parking at each penetration rate.

[b]Percent increase in total daily emissions and energy use are identical.

The low increases in total VMT and emissions at high penetration rates can be attributed to the fact that there are much more cars making trips in, out, and around Seattle than there are cars parked in the paid lots and garages in downtown Seattle during the day. At the highest AV penetration rate, about 30% of the AVs travel 10 additional miles per day, which is about a 90% increase in daily VMT compared to the existing average vehicle. While the numbers of AVs may be small relative to the whole system, if these routes are taken every day, then the extra travel would add to localized congestion. Fig. 3. (shown below) highlights the cumulative distribution of additional VMT by AVs with increasing market penetration rates. At 50% AV penetration, the cumulative probability that an AV selected at random would have traveled less than 5 miles for parking is about 40 percent, whereas at the 100% penetration rate the cumulative probability that an AV selected at random would have traveled less than 5 miles for parking is about 20 percent. In addition, this model only considers cars parked in lots and garages in downtown Seattle that have paid daily parking, so cars parked in employee or customer parking lots, cars occupying paid

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on-street parking spaces, or cars parked in paid garages and lots outside of downtown Seattle are not accounted for in this model. As fuel economy increases and/or cars become electrified, the relative per mile emissions and energy impacts would decrease further. However, the cars would have lower per mile operating costs and could travel further for cheaper parking, exacerbating impacts on VMT and congestion could be realized as the fleet becomes driverless.

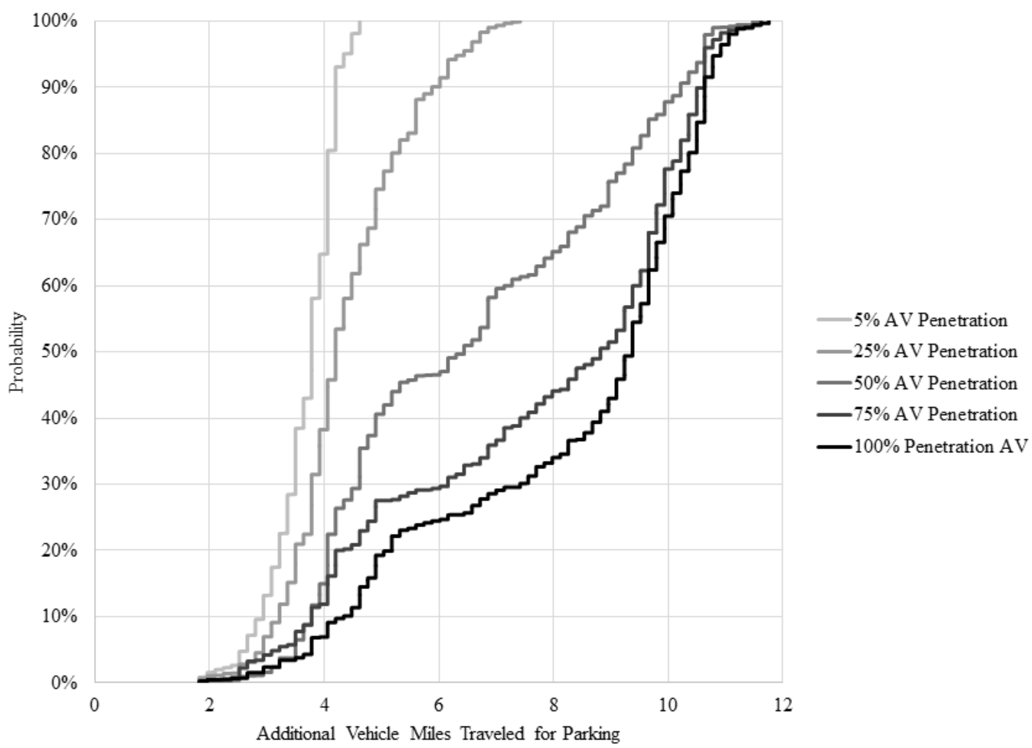

Fig. 3. Cumulative distribution of additional vehicle miles traveled for parking by AVs at increasing market penetration rates.

Table 5 displays the changes in the parking occupancy rates of the census blocks located within the downtown Seattle area with daily parking garages or lots as AV penetration rates increases. When there are no AVs in the downtown Seattle area, approximately 50% and 35% of the census blocks contain paid parking lots and garages with parking occupancy rates between 51%-75% and 76%-100%, respectively. At the 5% penetration rate, the number of census blocks with greater than 75% occupancy rates drops by about 30% while the number of census blocks with occuppancy rates between 51%-75% increases by about 16%. As the penetration rate increases to 75% just about all the occupancy rates drop below 25% and at 100% AV market penetration all cars would have shifted from paid parking to more distant, cheaper parking. The changes in parking occupancy for both paid and urestricted parking are illustrated below in Fig. 4, 5, 6 and 7. It should be noted thast this analysis assumes that all cars are willing to travel for cheaper parking and that the only determinants for a parking decision are economic costs and availability. At 50% AV penetration there arenoticeable increases the number of parking garages and lots with very low occupancy rates, between 1% and 25%. There is a direct relationship between the daily parking occupancy rate and daily parking revenue, and at 50% AV penetration and higher an increasing number of paid parking lots could become unprofitable.

Table 5. Downtown Seattle Daily Paid Parking Lot and Garage Parking Occupancy Rates from Increased AV Penetration Rates

		AV Penetration Rates					
		0%	5%	25%	50%	75%	100%
Parking Occupancy Rate	0%	0%	0%	0%	0%	0%	100%
	1%-25%	2%	3%	4%	13%	100%	0%
	26%-50%	11%	12%	38%	87%	0%	0%
	51%-75%	51%	59%	58%	0%	0%	0%
	76%-100%	36%	26%	0%	0%	0%	0%

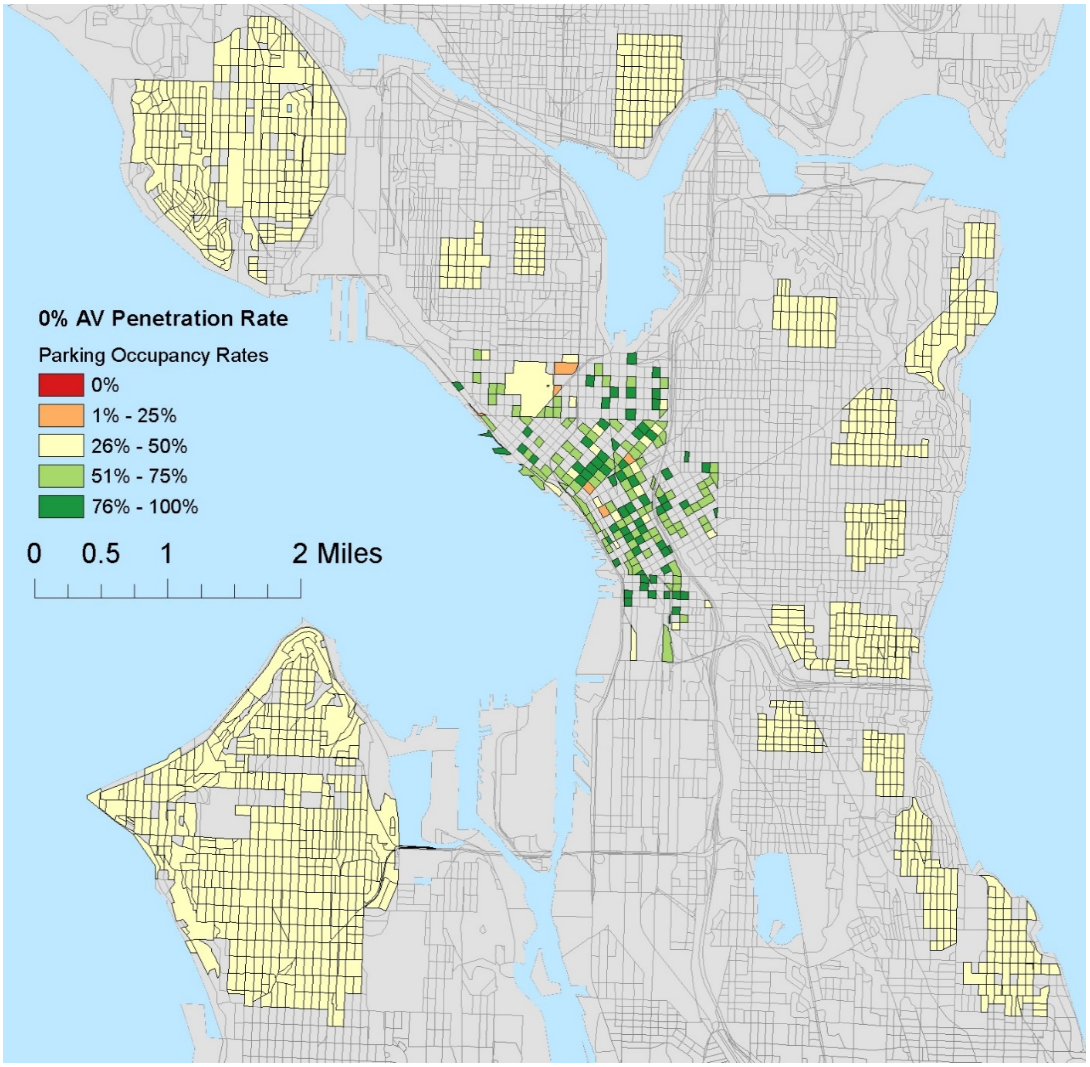

Fig. 4. Parking occupancy rates in Seattle at 0% driverless vehicle penetration

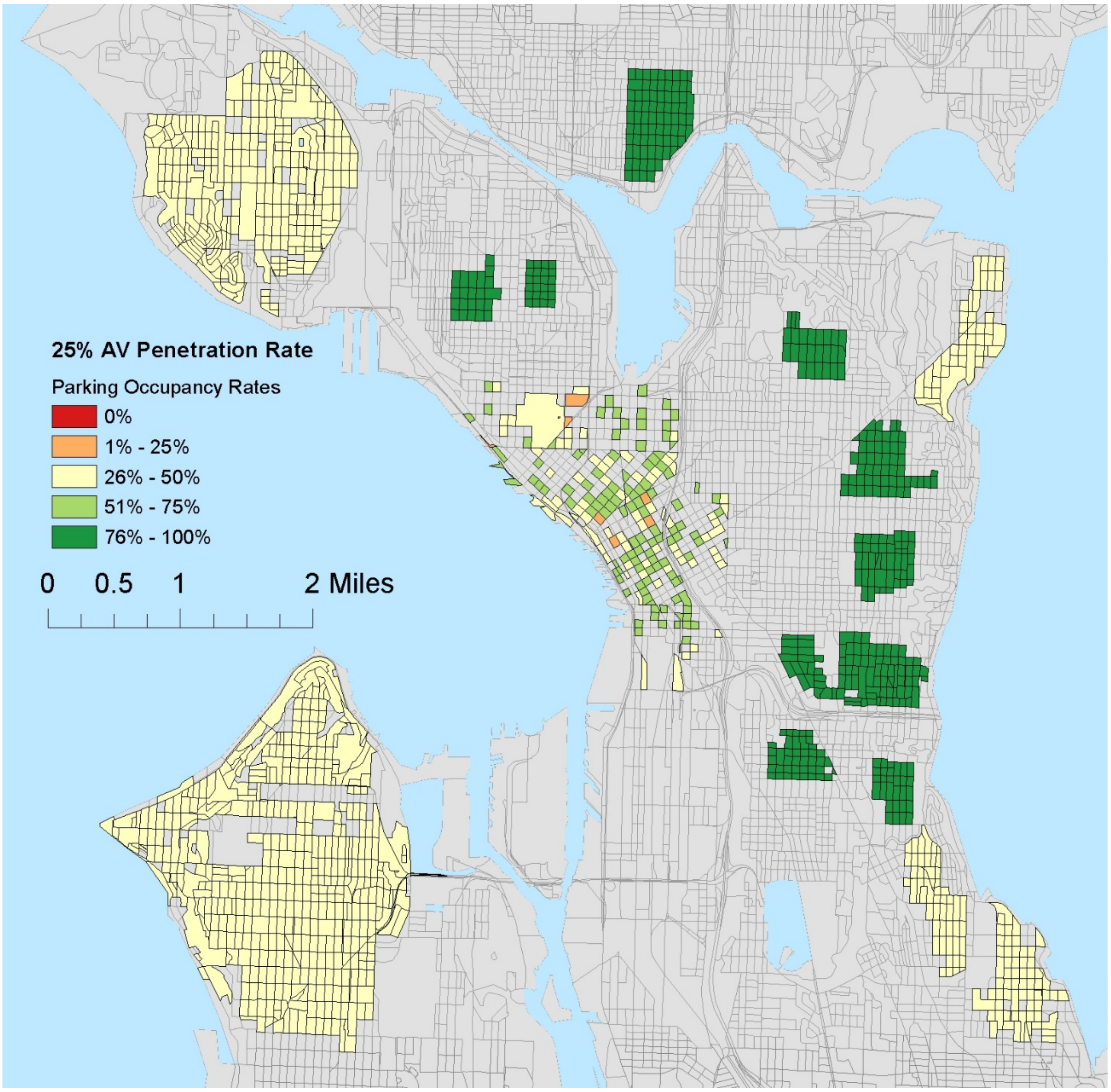

Fig. 5. Parking occupancy rates in Seattle at 25% driverless vehicle penetration

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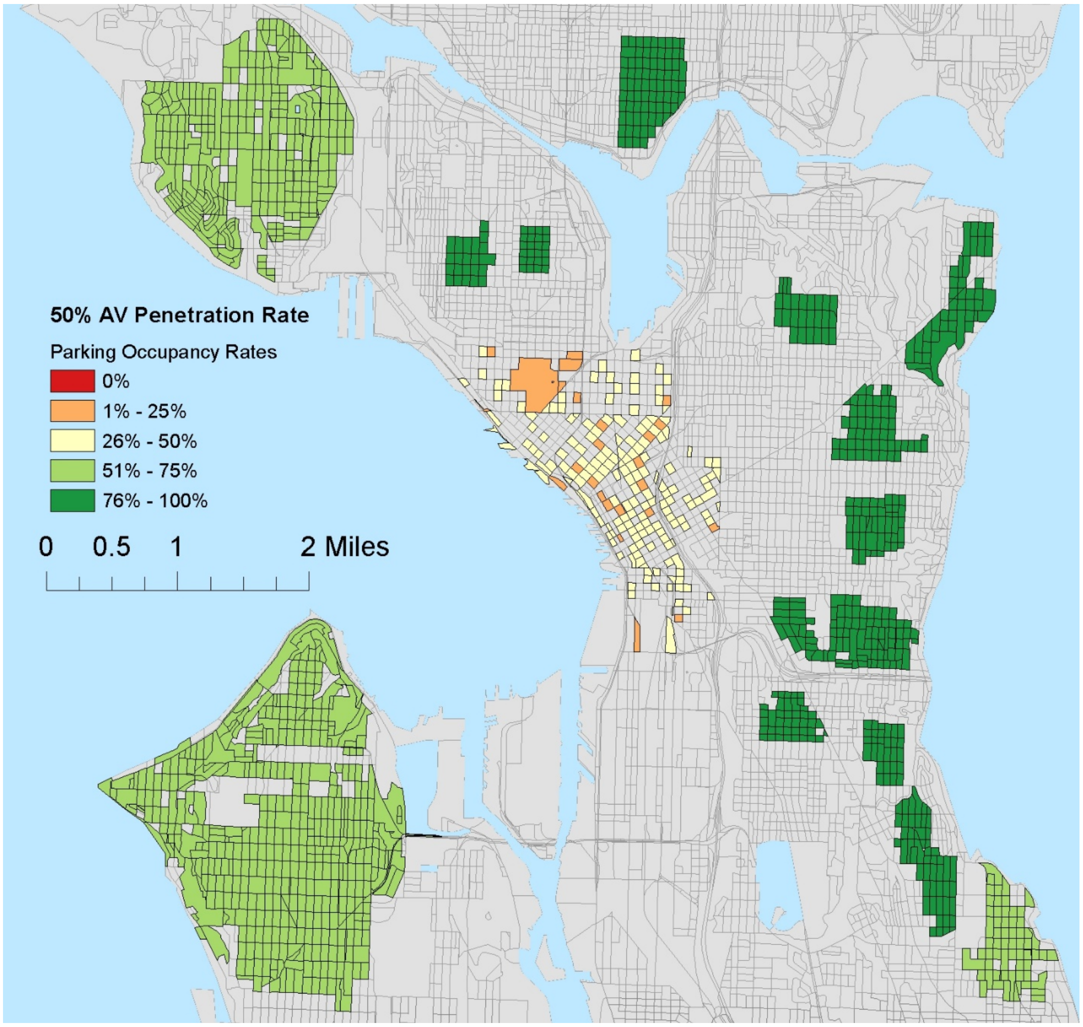

Fig. 6. Parking occupancy rates in Seattle at 50% driverless vehicle penetration

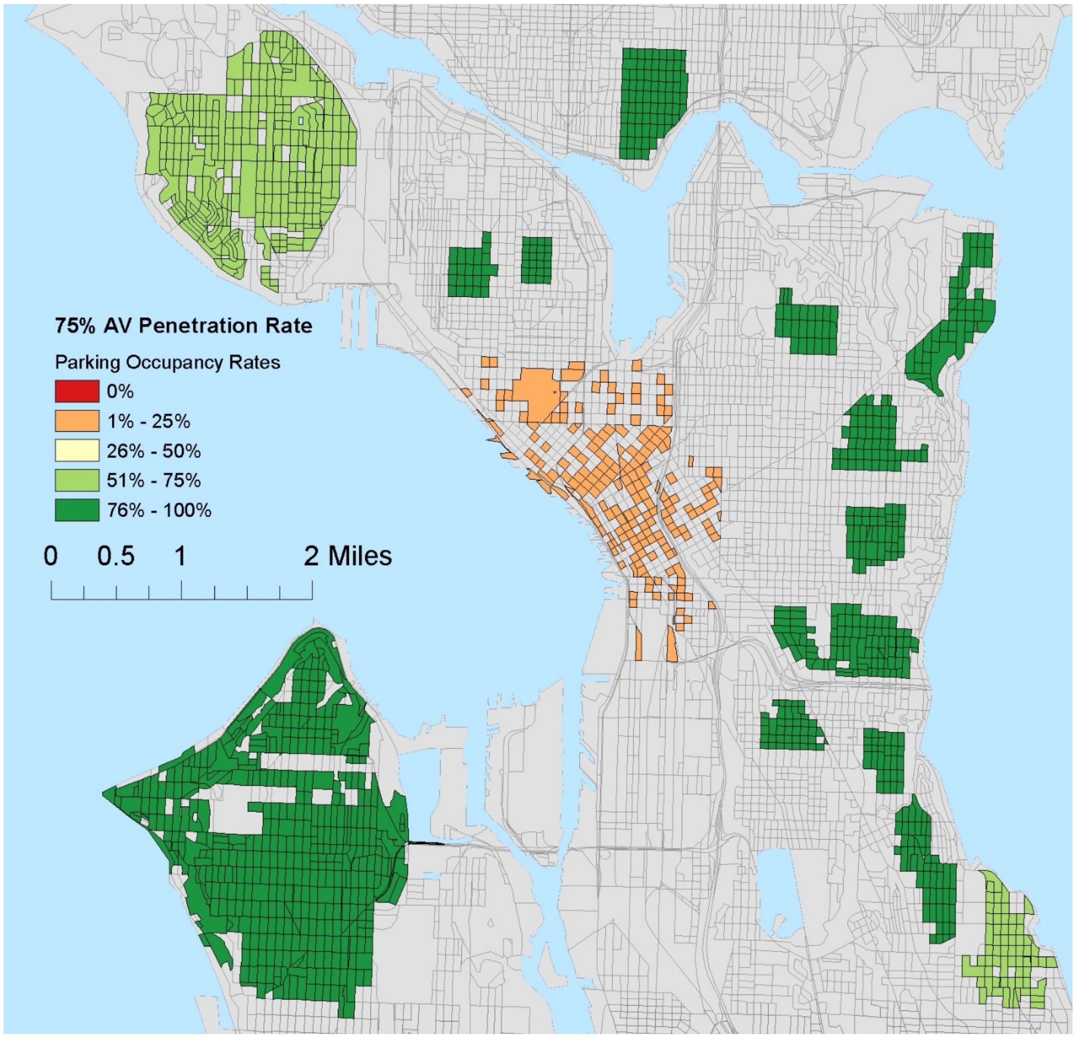

Fig. 7. Parking occupancy rates in Seattle at 75% driverless vehicle penetration

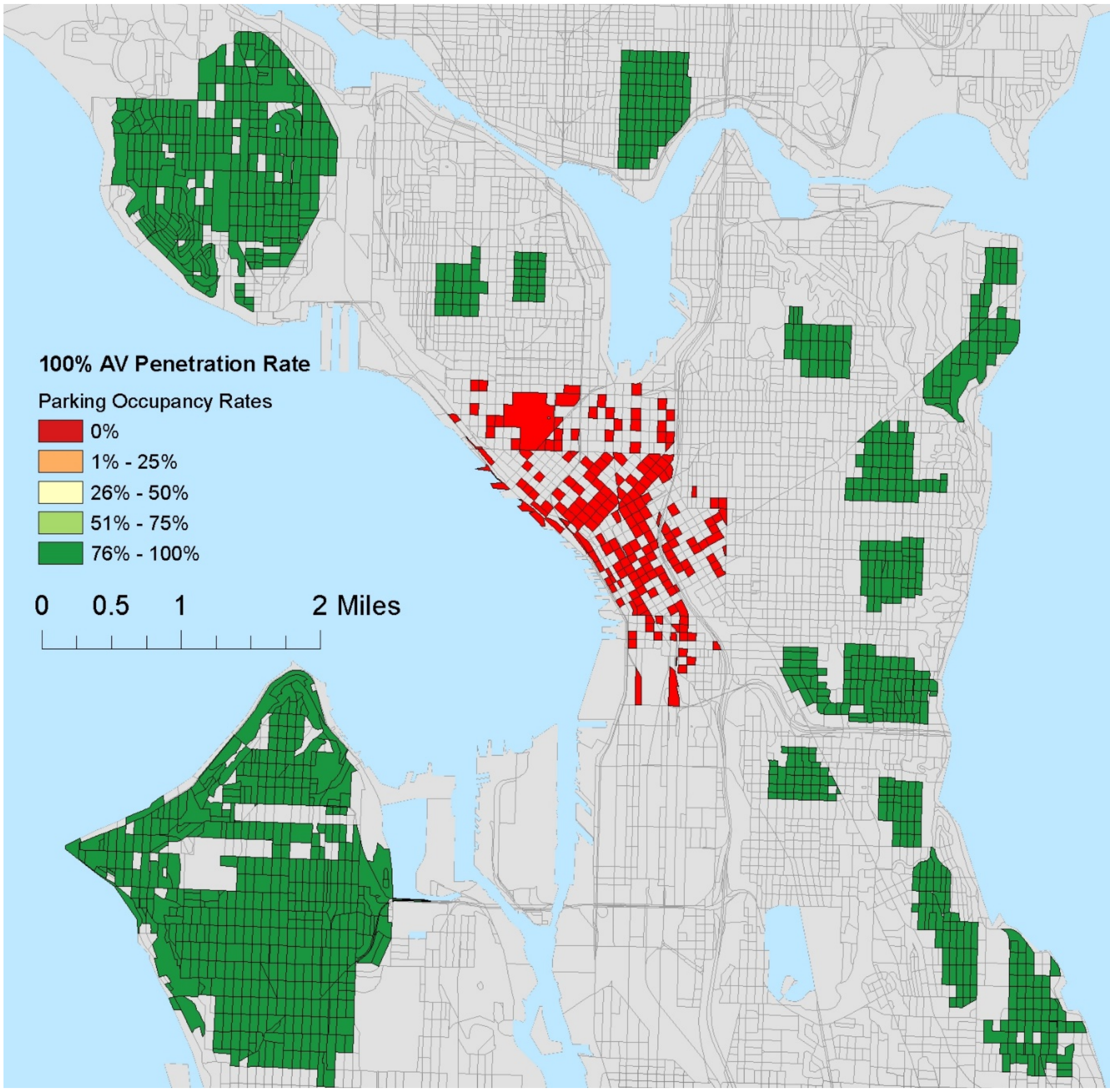

Fig. 8. Parking occupancy rates in Seattle at 75% driverless vehicle penetration

Sensitivity Analysis

The increases in VMT and emissions as well as the changes in parking occupancy rates are based on a variety of assumptions, the most significant being the AV penetration rate and the cost of driving. Changes in both categories could result changes in the parking decisions made by AVs. As shown, it is currently more economical for AVs to travel longer distances to obtain free parking than to park downtown in a paid parking lot. Different parking decisions could be made with a higher cost of driving, resulting from parking demand management strategies such as a parking tax for those AVs leaving the downtown area for parking, wasted fuel from congestion, and/or by enforcing parking restrictions in the UPZ. Traveling for cheaper parking outside of downtown is already economical, and scenarios where there is a lower cost of driving such as lowering the per mile cost of driving to than of an electric vehicle, would enhance the incentive economic incentive to travel longer distances for cheaper parking. In order to evaluate the impact other scenarios would have on the VMT as well as the parking occupancy rates in the downtown Seattle area, two-way sensitivity analyses were conducted to examine how changes in the cost of driving could impact AV parking decisions and travel patterns in Seattle. The range in the cost of driving represents the uncertainty associated with driverless vehicle technology costs, changes in fuel economy, changes in fuel prices, congestion/parking fees, emissions fees, or other internalized social costs.

Table 6 displays the sensitivity of Seattle's daily light-duty VMT to the AV penetration rate and per-mile cost of driving. At the 5 and 25 percent AV penetration rates, the increases in daily VMT are similar at most price points, which indicates unless there are significant increases in the cost of driving (either because of technology or policy), most AVs will choose to leave the downtown area and search for cheaper parking elsewhere at low penetration rates. This is due to the fact that at low AV penetration rates AVs are able to obtain their first ranked parking choice, which are usually relatively close to the downtown area. At the 50 and 75 percent penetration rates, the AV's decision to park away from the downtown area does not change until the per-mile cost of driving reaches \$1.50 and \$1.00, respectively. Similarly, at the 100% AV penetration rate AVs are less willing to travel far distances for free parking as the per-mile cost of driving increases. Although the per-mile operational cost of driving itself is not likely to reach above \$1 even in a fully AV environment, if Seattle chooses to implement a parking tax for AVs choosing to leave the downtown area for parking this would have an impact on parking decisions. The assumption that could have an impact on the VMT and emissions estimates is the amount of parking availability at each unrestricted parking zone (UPZ). The base case assumption for this model is that 50% of the parking spots in the UPZs are occupied by cars before the simulation begins and this assumption holds true for all penetration rates. If we increase the number of available parking spots at each UPZ, then more agents would obtain higher ranked parking choices, which would result in lower VMT and emission estimates, when compared to the estimates in the paper. Although, each AV would travel a shorter distance there is likely to be greater congestion implications since there would be a lot more AVs traveling to one destination during peak travel

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times. If we decrease the number of available parking spots at each UPZ, then less agents would obtain higher ranked parking choices, which would result in AVs traveling even further distances to obtain cheaper parking or remaining downtown if the cost of driving to travel to obtain free parking exceeds the daily cost to park and travel to the most economical parking lot or garage with parking availability. At the current operational cost of driving, AVs would be willing to travel up to 28 miles (includes round-trip distance and cruising), before choosing to park downtown where the least expensive daily parking spot is about $7.

Table 6. Percent Increases in Seattle Daily Light-Duty VMT from changes in AV Penetration Rates and the Per-Mile Cost of Driving

		AV Penetration Rate				
		5%	25%	50%	75%	100%
Cost of Driving ($/mile)	$0.25[a]	0.05%	0.30%	0.90%	1.70%	2.50%
	$0.50	0.05%	0.30%	0.90%	1.70%	2.50%
	$1.00	0.05%	0.30%	0.91%	1.60%	2.33%
	$1.50	0.05%	0.30%	0.68%	1.19%	1.73%
	$2.00	0.05%	0.28%	0.56%	0.63%	0.80%
	$2.50	0.05%	0.25%	0.42%	0.48%	0.57%

[a] Current per mile operational cost of driving a mid-sized sedan.

In addition, there is uncertainty associated with the model's assumption of perfect information of parking space status. The additional VMT associated with cruising for parking is known (e.g. Shoup et al. 2006), has a spatial and temporal component (Van Ommeren et al., 2012), and even moderate information or pricing provisions can reduce search time (e.g. Qian and Rajagopal 2014; Wang and He 2011)). Hence the likely upper bound of the uncertainty would be additional VMT from existing cruising for parking estimates, while in actuality the system would perform much closer that described in this paper due to parking system operator model. It is important to note that incorporating parking decision uncertainty into this model will not likely change the conclusions of this paper. If every single car parked in the downtown

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parking lots and garages became driverless and could self-park then there will be relatively small impacts to travel demand and energy use, in large part due to the relatively small number of cars parked in the downtown parking garages lots compared to the total number of cars making trips in, out, and around Seattle each day. Any additional cruising because of parking space uncertainty in the model is unlikely to affect the magnitude of the estimate, in a connected, automated vehicle environment.

Model Limitations

Although the simulation model adds understanding of how driverless cars may influence future urban parking and travel demand, the proposed AV parking model can be further improved from several perspectives. This study assumes that all AVs are aware of the amount of available parking in each UPZ and garage and lot, but this may not always be the case. Future modeling efforts should consider this and incorporate how AVs searching for cheaper parking without perfect information could impact VMT and emissions. Rather than using a gridded network to generate results, a more realistic road network could be incorporated to better capture the travel demand effects of these changes in parking decisions. Some users may also decide to continue to pay the higher parking price of parking in downtown garages due to the fact that curb parking does not provide shelter your car from inclement weather (rain, sleet, or snow) and extreme temperatures and sunlight. This analysis assumes that all cars are conventionally fueled, but in a fully AV environment many cars are likely to be electric vehicles, which means that the energy, emissions, and operational cost of driving (fuel and maintenance) could be further reduced. Downtown garages are likely to adjust their daily parking prices as customers begin to leave lots for cheaper parking, which is not accounted for in this analysis, but should be considered in future modeling efforts. Future analyses should also consider how increases in travel demand could impact travel time and congestion, especially at higher AV penetration rates where there is a mixed traffic flow. This study assumes that all AVs will travel to UPZs to obtain cheaper parking, but for those residents living close to or in downtown there are cases where sending the AV to back home to park is most economical choice.

While, this study assumes that all cars that traditionally park in downtown Seattle will search for cheaper parking if available, this may not always be the case. For example, users could deploy their cars for ridesharing during the day- picking people up and dropping them off- instead of searching for parking and vehicle ownership rates may change as drivers switch from personal to shared mobility. This study assumes that each AV adds 2 extra trips a day (traveling to and from a satellite parking location), but cars that act as shared mobility providers are likely to take more trips and travel more during the course of a day. Shared AVs could reduce energy use and emissions when compared to current light-duty vehicles by having the ability to right-size and reducing the number of vehicles on the road, but could likely increase VMT from the additional trips generated (Fagnant and Kockelman 2014; Greenblatt and Saxena 2015).

Conclusions

This study developed a simulation to evaluate the potential impact of driverless vehicles on VMT, emissions, parking revenues, and daily parking cost savings due to changes in parking decisions, using the 2013 PSRC Parking Inventory.

This model simulates the decision process that an AV could go through when deciding where to park in Seattle, ranking all of its parking choices based on economic cost, and calculating VMT, energy, emissions, and cost savings for each possible choice. The results indicate that AVs could substantially reduce daily parking costs by choosing to travel, sometimes far distances, to obtain cheaper parking instead of remaining in the downtown area and parking in a paid garage or lot. In comparison, as AV penetration rates increase and cars begin to leave the downtown parking lots for cheaper parking outside of the CBD, parking revenues decrease significantly, which means that operating and owning a parking garage or lot would likely become unsustainable from an economic perspective.

As the AV penetration rate increases, total VMT and energy use in the city of Seattle increases slightly. At low penetration rates AVs are usually able to obtain a higher ranked parking choice and as a result there are relatively small increases in VMT and GHG emissions. Even if all cars were driverless, the increase in VMT from cars leaving the downtown area to park in more distant parking locations is relatively small when compared to Seattle’s total daily light-duty VMT. The simulation estimates that at 100% AV penetration, Seattle’s daily light-duty VMT and GHG emissions would increase by approximately 2.5 and 2.1 percent, respectively. However, cars are willing to travel far distances to obtain cheaper parking. At the low penetration rates (5 to 25 percent AV penetration) AVs in Seattle would travel an additional 3.5 - 4.0 miles per day on average, and high penetration rates (50 to 100 percent AV penetration) AVs in Seattle would travel an additional 7.4 - 8.4 miles per day on average. The congestion that is generated from this extra travel is dependent on the time of day these trips are taking place and the corridors used to travel to parking destinations. Instead of congestion occurring from drivers cruising in search of an available parking spot in dense urban areas with scarce amount of parking, congestion could occur during peak hours from increased AVs on roadways traveling to distant parking locations. While the technology features of automated vehicles and connected infrastructure could alleviate some of this congestion, policy makers should plan for alleviating additional congestion from AVs.

At 50% vehicle automation, relatively significant increases in parking lots with very low occupancy rates are seen, which could lead to space that was once devoted to parking storage used for another purpose. The impacts of driverless valet parking on land use and safety is a relevant and timely topic that could be explored in more detail in future research. In addition, AV technology could lead to drivers switching from personal vehicle ownership to shared mobility services, further reducing the demand for parking (Fagnant and Kockelman 2015; Greenblatt and Saxena 2015; Zhang et al. 2015). Shared automated vehicles (SAVs) could reduce the number of cars on the road and after completing a trip would proceed to pick up the next passenger, instead of parking.

Finally, we also compared our model outputs to that of Fagnant and Kocleman (2014) and Zhang et al. (2015). Since those studies focus on SAVs, we only compare the VMT generated from unoccuppied trips. Zhang et al. (2015) estimated that a fleet of 650 SAVs could increase daily VMT anywhere between 210,000 and 340,000 miles, with each SAV traveling 320 to 520 additional miles a day from empty cruising. Their estimate is based on an agent-based model of a 16 x 16 km (10 mi × 10 mi) hypothetical city laid out in a grid network of 0.8 km (0.5 mi) street segments and is dependent on SAV fleet size, empy cruising time, and willingness of client agents (i.e. people who are willing to use the SAV system) to share. Fagnant and Kockleman (2014) estimated that a fleet of 1,700 SAVs could replace 20,000 POVs, but would increase daily VMT by about 11%, from empty vehicle travel. This study estimated that replacing manually driven

POVs with privately-owned AVs could increase travel demand in the city of Seattle by 2.5%, with each AV traveling about 8 additional miles a day from driverless valet parking technologies, at the highest penetration rate. That would suggest that empty vehicle travel from SAVs could generate far greater travel demand than POVs moving from downtown parking lots and garages to more distant and cheaper parking locations.

Currently, the main reason people use ride-hailing services are to avoid the hassles of parking (Clewlow, 2017) and with the introduction of driverless valet parking theoretically, this is no longer an advantage, since will still implicitly pay for parking, cruising, and all of the empty vehicle travel the SAV does. The advantages of an SAV are that one does not have to finance a car and make car payments, the elimination of driver cost, and sharing the cost of the trip with other users. But, if I own a Tesla with driverless capabilities and the cost of driving is low, am I going to give up my car for shared travel? Car owners may be willing to participate in the sharing economy by renting out their vehicles when it’s not in use. If drivers rented their cars out instead of having their car parked during the course of the day then this could have significant implications on daily Seattle VMT, because each car will travel substantially more than they would if they just simply parked in a more distant, cheaper parking location.

Regardless, the initial results suggest driverless valet vehicles will considerably alter the economics of parking, which will affect energy, emissions, and VMT in cities. Stakeholders could institute dynamic parking or roadway pricing policies to minimize extra VMT from AVs travelling outside of downtown to outer zones (and potentially back to the owner’s home) for cheaper parking. Automobile manufacturers and ridesharing companies are investing millions of dollars to make self-driving vehicles a reality. Policymakers, engineers, as well as urban planners should begin to consider the impacts of this technology on land and energy use, parking decisions, as well as public revenues so that society may have a smooth transition and minimize any negative consequences.

Notation

The following symbols are used in this paper:

AS= total number of available unrestricted parking spaces in each unrestricted parking zone;

$Avail_j$ = the parking availability at node j;

$Daily_j$= is the cost to park at node j for the duration of the day;

$Dist_{ij}$ = is the Manhattan distance from node i (your starting location) to node j (your parking destination);

$Drive$ = per-mile operational cost of driving a medium sized sedan;

$min\,TC_{ij}$ = minimum total cost from your starting point to your parking destination;

US= total number of unrestricted parking spaces;

P_{OS}= percentage of parking spots assumed to be already occupied by cars.

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