

# UCLA

## UCLA Previously Published Works

### Title

The autonomous vehicle parking problem

### Permalink

<https://escholarship.org/uc/item/2gm7843r>

### Author

Millard-Ball, Adam

### Publication Date

2019-03-01

### DOI

10.1016/j.tranpol.2019.01.003

### Copyright Information

This work is made available under the terms of a Creative Commons Attribution License, available at <https://creativecommons.org/licenses/by/4.0/>

Peer reviewed

# The autonomous vehicle parking problem

Preprint of manuscript published in *Transport Policy*

<http://dx.doi.org/10.1016/j.tranpol.2019.01.003>

January 2019

**Adam Millard-Ball**

Environmental Studies Department  
University of California, Santa Cruz  
1156 High Street, Santa Cruz, CA 95064  
United States

+1 831 459 1838

[adammb@ucsc.edu](mailto:adammb@ucsc.edu)

## Abstract

Autonomous vehicles (AVs) have no need to park close to their destination, or even to park at all. Instead, AVs can seek out free on-street parking, return home, or cruise (circle around). Because cruising is less costly at lower speeds, a game theoretic framework shows that AVs also have the incentive to implicitly coordinate with each other in order to generate congestion. Using a traffic microsimulation model and data from downtown San Francisco, this paper suggests that AVs could more than double vehicle travel to, from and within dense, urban cores. New vehicle trips are generated by a 90% reduction in effective parking costs, while existing trips become longer because of driving to more distant parking spaces and cruising. One potential policy response—subsidized peripheral parking—would likely exacerbate congestion through further reducing the cost of driving. Instead, this paper argues that the rise of AVs provides the opportunity and the imperative to implement congestion pricing in urban centers. Because the ability of AVs to cruise blurs the boundary between parking and travel, congestion pricing programs should include two complementary prices – a time-based charge for occupying the public right-of-way, whether parked or in motion, and a distance- or energy-based charge that internalizes other externalities from driving.

## Highlights

- Identifies and analyzes parking behavior of autonomous vehicles
- Uses a traffic microsimulation model to demonstrate how autonomous vehicles can implicitly coordinate to reduce the cost of cruising for parking, through self-generated congestion
- Discusses policy responses, including congestion pricing
- Argues that congestion pricing should include both a time-based charge for occupying the public right-of-way, and a distance- or energy-based charge to internalizes other externalities

## Introduction

The advent of autonomous vehicles (AVs) will revolutionize transportation (Sperling 2018). Safety is likely to be a primary benefit, along with increased mobility for the young, the elderly and people with disabilities. The environmental consequences are less certain: AVs may fuel urban sprawl, but generate opportunities to redesign streets for walking and cycling, and increase vehicle efficiency. In this paper, I identify and analyze a new channel through which AVs will have unambiguously negative environmental consequences—the removal of parking pricing, one of the most effective congestion management policies, from the urban transportation policy toolbox. AVs not only can avoid parking charges through cruising (that is, circling around while waiting for a passenger), but also have the incentive to seek out and exacerbate congestion—even gridlock—in order to minimize costs to their owners.

In almost every major city center, parking pricing is a key constraint on private car use, often as part of a wider suite of Transportation Demand Management policies. For trips to the city center, parking fees typically far exceed the cost of fuel, and are thus the main economic deterrent to driving. In Paris, for example, city-center parking costs USD35 per day; in Sydney, USD47; in Seoul, USD24 (Parkopedia 2017). The impacts of parking fees on travel behavior are well documented through empirical analysis, modeling studies and stated preference surveys (Vaca & Kuzmyak 2005). In the center of Portland, Oregon, for example, a \$6 daily parking fee reduces the drive-alone mode share from 62% to 46% (Hess 2001).

Road-user charging (often known as road or congestion pricing) may be the economically optimal policy to internalize congestion, air pollution and other externalities, but political and technological constraints have limited it to a handful of cities, most notably London, Singapore and Stockholm (Anas & Lindsey 2011). Parking pricing is a reasonable alternative to road-user charging that brings about similar benefits in congestion and vehicle trip reduction (Verhoef et al. 1995; Vaca & Kuzmyak 2005; Inci 2014).

In this paper, I show that the parking policies that have allowed dense, urban centers to flourish will no longer be a major curb on vehicle travel in an autonomous vehicle world. First, AVs remove the

parking proximity constraint: at high levels of automation,<sup>1</sup> AVs have no need to park close to their destination, or even to park at all. Second, AVs can behave strategically in order to minimize the costs to their passengers or fleet owners, primarily through seeking out and creating their own traffic congestion through choosing to circle on streets where they can drive the most slowly.

I focus on a scenario where vehicles are used primarily for the transportation of a single owner. An alternative future where AVs primarily consist of automated taxis – a “shared mobility” model – would partially mitigate the parking challenges identified here. However, a shared AV fleet would still render city-center parking charges impotent as a constraint on vehicle travel, as the traveler would not have to pay. Moreover, just as today’s taxis and ride-hailing vehicles often park during periods of lower demand, a fleet of shared AVs would require parking or would cruise around during at off-peak times.

The paper begins by briefly reviewing the existing literature to show how analysts to date have conceptualized the links between parking policy and autonomous vehicles. It then builds on previous research to set out an analytical framework with three mechanisms through which the inherent characteristics of AVs allow their owners or users to avoid parking charges. The paper then presents an empirical illustration, using a case study of downtown San Francisco to quantify the potential magnitude of AV parking behaviors, and employing a traffic microsimulation model to understand the congestion impacts of cruising vehicles. It concludes by discussing potential policy options, arguing that congestion pricing is the only feasible response.

## **Parking policy and autonomous vehicles**

The potential impacts of autonomous vehicles on vehicle travel and emissions are well documented in several comprehensive reviews (e.g. Wadud et al. 2016; Milakis et al. 2017). In short, several competing effects make it hard to predict the net outcome with any degree of certainty. As Wadud et al. (2016, p. 1) conclude, “automation might plausibly reduce road transport GHG emissions and energy use by nearly half – or nearly double them – depending on which effects come to dominate.” The reduced time cost of vehicle travel is likely to promote more and longer vehicle trips, as drivers are able to work or undertake other activities during a trip. The effective increase in roadway

---

<sup>1</sup> This paper considers automation levels where a human driver is not required in certain environments, equivalent to Level 4 or 5 under the SAE classification system. See [https://www.sae.org/standards/content/j3016\\_201609/](https://www.sae.org/standards/content/j3016_201609/)

capacity, due to the ability of AVs to drive closer together and in narrower lanes, is likely to induce additional travel through reducing congestion. Further vehicle travel increases will come from increased mobility among people who cannot currently drive a car due to age or disability. On the other hand, AVs are likely to be more energy efficient, and may make shared trips more feasible if privately owned vehicles are replaced by a fleet of shared AVs.

A more far-reaching channel through which AVs may alter travel demand is through their impacts on urban development. By freeing up land that is currently devoted to parking, AVs will permit increased development densities, in turn allowing urban centers to become more pedestrian oriented, and reducing the pressures for urban sprawl on the metropolitan periphery (Fagnant & Kockelman 2015; Levinson 2015; Anderson et al. 2016; Milakis et al. 2017). The maneuverability of AVs allows parking spaces to be smaller and consume less land (Nourinejad et al. 2018), and AVs can also park in peripheral areas or circle around in lieu of parking. More dramatic reductions may be possible if AVs are shared rather than privately owned; several modeling studies suggest that parking demand could be reduced by up to about 90% in scenarios where all AVs are shared (Fagnant & Kockelman 2014; Zhang et al. 2015; Zhang & Guhathakurta 2017; Martinez & Viegas 2017). One of the most widely cited studies suggests that “almost eleven parking spaces can be eliminated for every SAV [shared AV]” (Fagnant & Kockelman 2014, p. 8).

Indeed, developers, municipalities and financial markets are already responding to the potential impacts of AVs on parking demand. New buildings in places such as Cincinnati and Denver feature parking garages that can be retrofit to residential or commercial space should parking demand fall in the future (Grant 2018). The City of Chandler, Arizona, allows up to 40% of required parking to be substituted by loading zones for passenger pick-up and drop-off, in recognition of the advent of AVs and app-based taxi services (Maryniak 2018). Bond investors, meanwhile, have expressed concerns about garage financing schemes that rely on future parking revenue streams (Courtney 2018), and one firm advises that “an ultimate 50% reduction [in parking demand] in 30 years seems like a reasonable outlook for real estate investors to consider” (Bragg & Pazzano 2018, p. 13).

The impacts of AVs on parking behavior, however, are often assumed or mentioned in passing rather than carefully analyzed. A common notion is that because AVs *can* drop off their passengers and park remotely, they *will* do so in practice. And while cruising is often mentioned as a strategy for

AVs to avoid parking charges, there is little analysis that identifies when and where cruising may be a preferred option.

In practice, the decisions by AVs regarding parking location and whether to park or cruise are likely to be economically driven, and based on the relative costs of each option. Only two studies explicitly model such decisions. Zakharenko (2016) considers parking choices between the central business district, a peripheral “parking belt,” and returning home. His analytic model of an idealized city suggests that up to 97% of commuter AVs would choose the peripheral parking belt, which would take advantage of lower land prices just outside of the commuter work zone. Harper et al. (2018), meanwhile, use parking price and occupancy data from Seattle in an agent-based model that simulates the choice between parking in downtown or in remote spots. They find that remote parking would save AV users about \$18 in daily parking costs, and increase vehicle travel by 2.5% due to the roundtrip between the downtown destination and the parking facility.

Neither study, however, analyzes the option of cruising for parking as an alternative to peripheral parking, and Harper et al. do not consider the “return home” option either. Nor does either study analyze the impacts of reduced parking costs on trip making. Indeed, the last limitation is shared with most of the wider AV travel demand literature, which focuses on how a reduced value of travel time promotes longer trips, but neglects the impacts of changes in parking costs. One notable exception models a scenario where parking costs are halved to reflect the ability of AVs to park in cheaper locations and in smaller spaces (Childress et al. 2015), but even here, the parking cost reduction is somewhat arbitrary.

The following section, therefore, develops an analytical framework with three channels through which AVs could avoid paying for parking. The subsequent empirical illustration quantifies the importance of each channel, and estimates the direct impacts on vehicle travel from use of remote parking facilities or cruising, and the indirect impacts through reducing the effective cost of parking to travelers.

## **Analytical framework: Three channels to avoid parking fees**

AVs could certainly continue to park as human-driven vehicles currently do. Where cars currently park for free, as is the norm in many countries outside city centers, there is no reason for automation to change this behavior. Where parking incurs a charge, however, autonomy opens up alternative parking strategies.

First, AVs can park in peripheral locations, as assumed or analyzed by many of the studies discussed above (e.g. Zakharenko 2016). If dedicated remote parking facilities are provided free of charge, this may be an enticing option for AVs that only incur the roundtrip cost between parking and the user's destination. Otherwise, however, AVs may simply saturate existing reservoirs of on-street parking throughout the city. In most U.S. cities, on-street parking is managed through a combination of (i) meters on commercial streets, and (ii) permit programs on residential streets which provide unlimited parking to residential permit holders and free two-hour parking to visitors. At present, a meter-and-permit system works well in discouraging commuter parking. But AVs can simply park for free in a two-hour space, and move around every two hours. Alternatively, there is little to stop them from parking at a meter (which, without a human present, they cannot feed) and keeping a watchful eye for a parking enforcement officer.

Revamping their management of on-street parking is perhaps an easy fix for cities to make. After all, the first parking meter was installed in Oklahoma City in 1935 to make it easier for shoppers to find a space, after parking spaces in front of businesses began to be monopolized by all-day employee parking (Erickson 2012). In response to AVs, cities could simply eliminate free parking, or even use the advent of AVs to remove on-street parking altogether in favor of repurposing streets for wider sidewalks, street cafes and other public spaces (Schlossberg et al. 2018). Payment technology, meanwhile, could be adapted to allow the use of in-vehicle meters that could be activated without the need for a human presence. However, such regulatory responses may take time to implement, and are far from assured.

A second approach by which AVs may avoid paying for parking is harder for cities to combat through regulatory restrictions. An AV could simply go home after dropping off its passengers and return to its residential parking space that is free or paid for on a monthly basis. An AV adopting this strategy would double the amount of driving per trip. This is referred to as "Type III parking" by Zakharenko (2016).



A third option—cruising, where an AV circles around while waiting for a passenger—would also increase the amount of driving per trip, and be similarly difficult for cities to combat through regulation. The ability of AVs to cruise blurs the boundary between parking and travel. An instructive analogy is to airport parking after the widespread adoption of mobile telephones. Whereas drivers picking up an arriving airline passenger might previously have paid for short-term parking, mobile phones allowed them to avoid parking fees by circling around the terminal buildings (Kramer & Mandel 2015).

All three of the options above have been identified in previous studies, although not necessarily as part of a unified framework. However, one element that is missing from discussions to date is a recognition that the owners and designers of AVs have every incentive to engage in strategic behavior to reduce the cost of cruising, at the expense of exacerbating congestion. While vehicles tend to be less efficient *per mile* of travel at slower speeds, slower speeds are more cost effective when the objective is to reduce the cost *per hour* (Figure A-1). Thus, AVs trying to pass time by cruising, and doing so at the least cost, will seek out congested traffic. This is particularly true for battery-electric vehicles, where the efficiency penalty for slower speeds is less than for vehicles with internal-combustion gasoline engines.

In economic terms, AVs will play a coordination game. Multiple cruising vehicles will have lower costs if they choose the same set of streets to circle around, thus congesting each other's paths. With a simple vehicle-to-vehicle communication system, the agreed-upon set of streets would in effect be transformed into a mobile and very slow-moving parking lot. Given such congestion, even today's electric vehicles with limited battery capacity and range could cruise for most of the day. Even if communication between AVs is legally prohibited, the same congested equilibrium can arise through decisions by individual cost-minimizing AVs. Suppose that at each intersection, the AV chooses the most congested street. Over time, AVs would converge on the same set of streets to circle while waiting.

## **Empirical illustration**

Each of the three channels discussed above is a plausible response by autonomous vehicles as they take advantage of new parking options. The mix of AV responses, however, will depend on the relative costs of each option, and particularly whether it is feasible for AVs to reduce cruising costs through seeking out or creating congestion. To provide an empirical illustration of the potential importance of each channel, I use the case of downtown San Francisco, which has long employed parking policy to constrain private automobile travel to downtown, and perhaps as a result, has unusually high-resolution data on parking supply and occupancy. I focus on downtown because most other areas of the city have much lower or even zero parking prices, and thus there is little reason to expect AVs to seek to avoid paying for parking. I analyze the user cost of employing the three alternative parking strategies—free on-street parking, returning home, and cruising—discussed above. For each trip to downtown San Francisco, costs are estimated based on the user’s destination, length of stay, and parking costs.

## **Data and methods**

Unless specified, all data are from the SF-CHAMP activity-based transportation model, maintained by the San Francisco County Transportation Authority (SFCTA), except for the street network which is from OpenStreetMap. The trips are for a representative weekday in 2015 and include vehicle trips that have an origin or destination in downtown San Francisco. The last trip of the tour (normally the return home) is excluded, along with trips where the home TAZ is the same as the destination TAZ (which are assumed to have a zero parking cost). Limiting the analysis to downtown captures the area of the city where parking costs are highest (Figure 1). Origins and destinations are aggregated to SFCTA-defined Transportation Analysis Zones (TAZs), of which there are 109 in downtown San Francisco, and 2245 in the San Francisco Bay Area as a whole. Table 1 summarizes the trip-level data, and also shows the baseline parking costs. At present, two-thirds of daily private vehicle trips to downtown incur a parking charge, which averages \$1.28 per hour or \$4.66 per trip. (These costs are averaged over all trips, including those with free parking.)

The marginal costs of vehicle travel are a key input to the parking choice analysis, and are derived separately for electric vehicles (EVs) and internal-combustion (gasoline) powered vehicles using previous research studies. The Appendix provides full details.

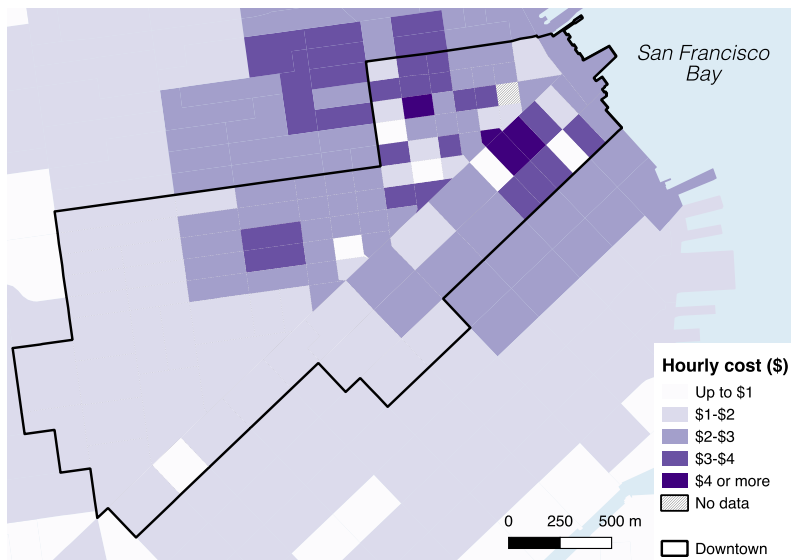
**Table 1 Summary of vehicle trips to downtown San Francisco**

	N	Per cent
Vehicle trips	86,453	100.0
– 0300–0600	4,659	5.4
– 0600–0900	24,447	28.3
– 0900–1530	34,192	39.5
– 1530–1830	14,421	16.7
– 1830–0300	8,734	10.1
Mean trip duration (hours)	3.6	
Mean trip length (km)	18.3	
Paid parking	52,418	60.6
Free parking	34,035	39.4
Mean parking cost per hour*	\$2.94	
Peak parking demand**	30,090	

\*Trips that incur a parking charge

\*\* Calculated based on trip departure times and durations

**Figure 1 Hourly cost of work parking**



Source: Data from San Francisco County Transportation Authority

### *Strategy 1: Free on-street parking*

There are ~249,000 unmetered on-street parking spaces in the City of San Francisco, of which ~80,000 are under Residential Permit Parking (RPP) restrictions (SFMTA 2014; SFMTA 2017). City of San Francisco surveys indicate that RPP spaces are 86% occupied on an average weekday morning (SFMTA 2017), leaving ~11,000 spaces available for autonomous vehicles.

Occupancy levels within the ~169,000 on-street spaces on unregulated blocks are likely to be lower than those on RPP-regulated blocks, given that RPP programs are established where occupancy is high. Applying the RPP occupancy (86%) to unregulated spaces is therefore a conservative approach, which yields an estimate of ~24,000 unregulated spaces available for autonomous vehicles. The supply of on-street parking, then, is more than sufficient to accommodate all the vehicles in downtown that currently pay for parking at the peak hour. There are ~35,000 on-street spaces to accommodate the ~18,200 vehicles at peak (60.6% of 30,090, as in Table 1) that currently pay for parking.

The cost of an AV to drive and park in a free on-street space therefore consists only of the costs of driving to and from the space. (The negligible cost for the AV to leave a time-limited space and repark every two hours, if necessary, is ignored.) For each trip, the pgrouting software package is used to calculate the roundtrip network distance between the destination TAZ and each block with residential permit parking. The mean distance is used, meaning that the estimates should be interpreted as expected values. The per-km driving costs from Table A-1 are then applied. Trips where the length of time at the destination is insufficient to permit a roundtrip to the mean on-street space (based on an average speed of 40 km hour<sup>-1</sup>) are excluded from this analysis. The approach here is similar to Harper et al. (2018), except that the authors in that paper model the choice between different parking garages, rather than considering the reservoir of free on-street parking.

For example, take a trip to the Ferry Building in downtown San Francisco. The median RPP block is 5.6km distant. At a driving cost per km of \$0.13 (assuming an EV), the roundtrip cost to take advantage of free on-street parking would be \$1.46.

### *Strategy 2: Return home*

A “return home” strategy assumes that the AV has access to a free parking space (or a space paid for on a monthly basis) at home. For each trip, the pgrouting software package is used to calculate the

roundtrip network distance between the destination TAZ and the home TAZ. The per-km driving costs from Table A-1 are then applied, plus a bridge toll if applicable. Trips where the length of time at the destination is insufficient to permit a return home (based on an average speed of 40 km hour<sup>-1</sup>) are excluded from this analysis.

### *Strategy 3: Cruising*

The cost per hour of cruising is speed dependent. While calculations could use current vehicle speeds from San Francisco's congestion monitoring program, this would not account for the ability of AVs to reduce travel speeds and hourly cruising costs through seeking out congested traffic and clustering together. Therefore, I estimate speeds using the SUMO open-source traffic microsimulation model (Krajzewicz et al. 2012). In order to isolate the impact of AV parking strategies on traffic flows, only cruising vehicles are modeled, and pedestrians, bicycles, buses and freight vehicles, along with traffic traveling to and from a destination, are not included in the simulation. In practice, this means that modeled speeds are much greater than they would be in reality, since any congestion is caused by the cruising vehicles themselves; there are no pre-existing delays.

The cruising vehicles have origins drawn from the distribution of destination TAZs in downtown San Francisco, according to the SF-CHAMP model files. A total of 7,500 vehicles are inserted into the SUMO model, starting at a random edge within the destination TAZ, at two-second intervals. The simulation itself uses a one-second time resolution. The road network is based on OpenStreetMap data.

Cruising behavior is modeled through a mechanism that allows vehicles to lower their hourly cruising costs through seeking out congestion, without the need for any coordination between vehicles. At each intersection, the vehicle chooses to continue onto the edge (i.e., street segment) with the lowest travel speed, or in the event of a tie, the edge with the greatest number of vehicles.

The exceptions are as follows:

- Dead-ends and U-turns are not chosen, unless there is no other option.
- A vehicle will not choose an edge where there are at least 10 vehicles, all vehicles are stationary, and the edge occupancy (length of vehicles divided by length of lanes) is greater than 50%. This helps vehicles avoid gridlock conditions under which they may be unable to return in time to pick up their passenger. (This constraint is removed in the "possible gridlock" sensitivity test reported below.)

- With 1% probability, the vehicle chooses the next edge at random, in order to prevent the simulation becoming “stuck.”

For comparison, a sensitivity test is also run in which vehicles make turns at random, rather than seeking out congested traffic.

With the exception of the cruising behavior described above, the default SUMO parameters are used to model behavior such as lane changing, yielding, acceleration and braking, and gaps between vehicles. In practice, AVs are unlikely to behave in the same way as existing vehicles. Indeed, traffic signals and stop signs may be eliminated in an AV future, and autonomous vehicles may be able to increase intersection capacity by more than 40% due to increased turning speeds (Liu et al. 2018). Further increases in capacity may arise from reduced gaps between vehicles in intersections (Friedrich 2016) and increased stability of traffic flow (Mahmassani 2016). Set against this, cruising AVs have the incentive to drive as slowly as possible, for example through leaving larger-than-normal gaps between vehicles, and displaying exaggerated courtesy to other vehicles, pedestrians and cyclists. In the absence of any firm information on how AVs will affect roadway capacity, current driving behavior provides a good baseline.

Figure 2 (solid green line) shows how the speeds of cruising vehicles change with the number of vehicles in the simulation. Even a few hundred cruising vehicles are able to find each other through choosing to turn onto streets with the lowest speeds, but speeds continue to decrease as more vehicles are added to the streets. By 4,000 vehicles—representing less than 15% of peak parking demand—cruising speeds have fallen below 2 km h<sup>-1</sup>. There are about 40,000 parking spaces in downtown San Francisco, and so 4,000 vehicles also represent a small fraction of the current parking supply.

Figure 2 also presents two sensitivity tests. The dashed orange line shows a simulation where vehicles make turns at random, without attempting to find the slowest streets. In this simulation, speeds also decline with vehicle numbers as traffic congestion increases, but the gap between the “cruising” and “random turns” simulations indicates the effectiveness of the strategy to choose the most congested streets, which reduces speeds by ~5 km h<sup>-1</sup>. The dashed purple line shows the “possible gridlock” simulation, where the constraint that AVs may not turn onto the most congested streets is removed. Here, speeds fall to <0.5 km h<sup>-1</sup>. While in most circumstances, cruising AVs may avoid overly congested streets (so that they can return to pick up their user within a reasonable

amount of time), this may not be a constraint should a U-turn allow a vehicle to extricate itself from the situation.

For comparison, streets in downtown San Francisco had an average speed of 8.7 mph or 14.0 km h<sup>-1</sup> in 2017 in the afternoon peak, according to the San Francisco County Transportation Authority congestion monitoring program. However, streets in the monitoring program consist of arterials, where traffic signals are timed and speeds are higher compared to the network as a whole.

Figure 3 maps speeds (as a fraction of free-flow speed for each edge) and vehicle densities (i.e., edge occupancies, defined as the length of vehicles divided by length of lanes). It is evident that the low speeds and high edge occupancies are limited to a small fraction of the downtown street network, further indicating the success of cruising vehicles in finding congested traffic, even without explicit coordination. A video showing part of the simulation (on Harriet/Bryant/6<sup>th</sup>/Brannan streets in San Francisco’s South of Market neighborhood) is provided in the Supplementary Information.

The remainder of the analysis assumes that cruising vehicles can lower their speeds to 2 km hour<sup>-1</sup>. Combined with the speed-dependent driving costs in Table A-2, this implies a cost per hour of cruising of \$0.48. Two sensitivity tests assume a cost per hour of cruising of \$0.29 (under the “possible gridlock” simulation, where speeds fall to 0.5 km hour<sup>-1</sup>), and \$1.98 (based on the monitored average speed of 14.0 km hour<sup>-1</sup> reported above).

**Figure 2**      **Speeds of cruising vehicles**

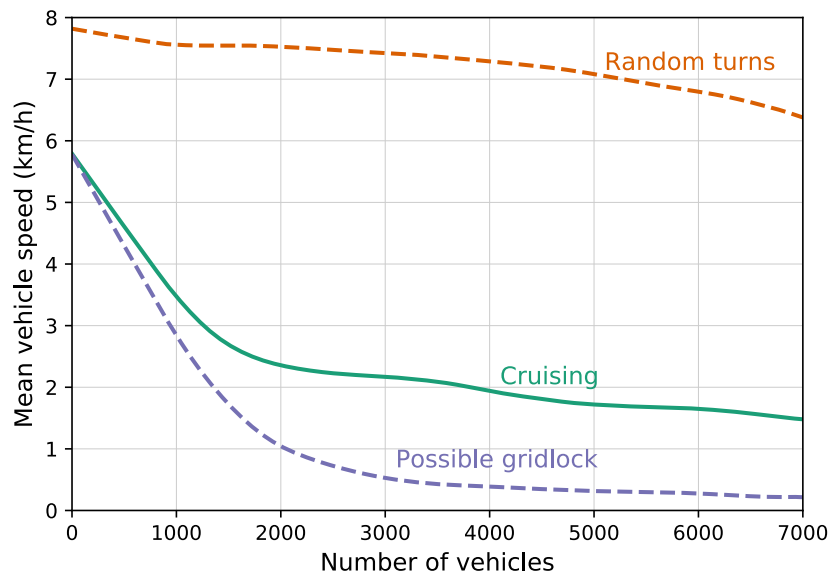
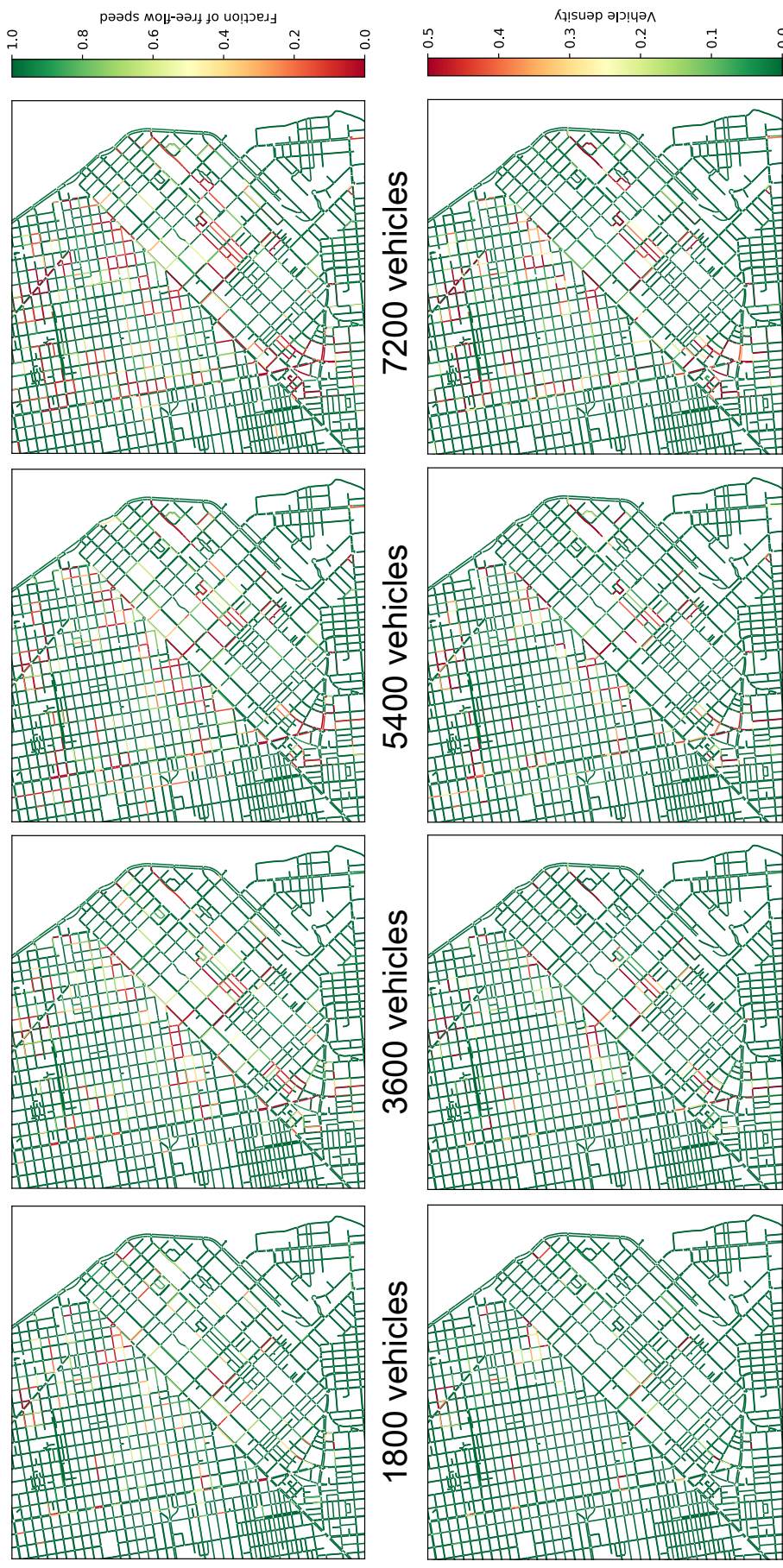


Figure 3 Simulated speeds and edge occupancies





## **Results: AV parking choices**

For each vehicle trip to downtown San Francisco, the cost of each option—continuing to park as before, or adopting one of the three new AV parking strategies—is calculated using the methods discussed above. I assume that each trip adopts the lowest cost option. The results are shown for electric vehicles in Table 2 and Figure 4, and the remainder of the discussion focuses on these EV results. However, the distribution of lowest-cost approaches is similar for gasoline-powered internal-combustion vehicles (Table 3).

Nearly 40% of trips to downtown already enjoy parking at no cost (normally, provided by an employer), and these trips continue to park as before, rather than switching to an alternative AV parking strategy. Free on-street parking is the cheapest option for 13% of trips. This option is generally preferred for longer stays, as the cost is independent of the length of time parked. Returning home is only adopted for 8% of trips. It is the lowest-cost option for the small fraction of trip-makers who live close to downtown and have short stays at the destination, but otherwise it is generally an expensive strategy given the mean distance from the downtown destination to home of 18.3km.

For the plurality of trips (40%), cruising is the cheapest option, and reduces the effective cost of parking to less than 50 cents per hour. In practice, costs may be even lower; in the “possible gridlock” simulation, costs fall to 29 cents per hour. At the limit, cruising costs approach \$0 if AVs are able to be at a standstill for almost the entire time period.

Overall, removing the parking proximity constraint allows AVs to reduce mean “parking” costs substantially, from \$4.66 to \$0.48 (90%) on a per-trip basis, or from \$1.28 to \$0.13 (90%) on a per-hour basis. Cruising provides an effective cost ceiling of \$0.48 hour, but many trips incur costs below this level.

**Table 2 Lowest-cost parking option (battery-electric vehicles)**

	Number of trips	Per cent of trips	Average cost per hour	Average cost per trip	Excess vehicle km per trip
Park as before	34,051	39.4	\$0.00	\$0.00	0.0
Free on-street parking	11,007	12.7	\$0.22	\$1.34	10.3
Return home	6,859	7.9	\$0.20	\$0.65	5.0
Cruise	34,536	39.9	\$0.48	\$0.64	2.7
All strategies	86,453	100.0	\$0.13	\$0.48	2.8

*Each row refers to the subset of vehicle trips that adopt each strategy.*

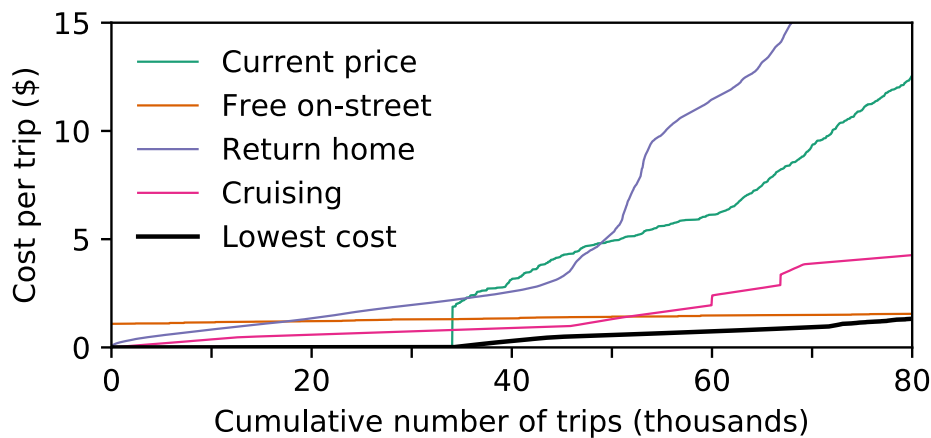
**Table 3 Lowest-cost parking option (internal-combustion vehicles)**

	Number of trips	Per cent of trips	Average cost per hour	Average cost per trip	Excess vehicle km per trip
Park as before	34,054	39.4	\$0.00	\$0.00	0
Free on-street parking	12,477	14.4	\$0.34	\$1.96	10.3
Return home	7,946	9.2	\$0.32	\$0.99	5.2
Cruise	31,976	37.0	\$0.83	\$1.05	2.5
All strategies	86,453	100.0	\$0.21	\$0.76	2.9

*Each row refers to the subset of vehicle trips that adopt each strategy.*

**Figure 4 Distribution of costs for alternative AV parking strategies**

*The cumulative distribution of current parking prices and each of the three alternative parking strategies are shown, along with the lowest-cost of the four options. Costs > \$15 per trip are not shown.*



The impacts of the price reduction on vehicle travel can be estimated using standard parking price elasticities. Based on a typical parking price log arc elasticity of -0.3 (Vaca & Kuzmyak 2005), the change in vehicle trips can be calculated using the following formula (Pratt 2013):

$$\eta = -0.3 = \frac{\log Q_2 - \log Q_1}{\log P_2 - \log P_1}$$

Where  $\eta$  is the elasticity,  $P_1$  and  $P_2$  are the prices in periods 1 and 2, and  $Q_1$  and  $Q_2$  are the quantities (number of vehicle trips) in periods 1 and 2. Given the price change from \$4.66 to \$0.48 per trip and the elasticity of -0.3, we obtain  $\log Q_2 - \log Q_1 = 0.683$ , so 100 vehicle trips in period 1 would increase to 198 in period 2, or a 98% increase. Given the richness of public transportation alternatives in a downtown environment, traveler responses may be greater; a (later reversed) reduction in San Francisco’s parking tax, from 25% to 10%, led to an almost-proportionate increase in driving by commuters, and a smaller increase by shoppers (Vaca & Kuzmyak 2005, p. 13-41).

Meanwhile, a further 2.8 km in excess travel per trip results from vehicles returning home, driving to free on-street parking spaces, or cruising, as shown in Table 2. The 2.8 km is equivalent to an 8% increase in vehicle travel, based on the mean roundtrip distance of 36.3 km for vehicle trips to downtown San Francisco. In combination, the price effect and the excess travel effect yield an increase of 106%. Vehicle travel to, from and within downtown San Francisco would more than double.

Cruising, counterintuitively, would have a greater impact on congestion than on vehicle travel, given that cruising AVs have the incentive to travel as slowly as possible and thus would drive relatively few kilometers in any given hour. In the San Francisco simulation, fewer than 4,000 AVs are enough to slow certain streets to below 2 km h<sup>-1</sup>, partly because cruising vehicles are concentrated on particular streets. The video (provided as supplementary information) provides a graphic example of the dynamic behavior.

Table 4 presents a sensitivity analysis using different assumptions for cruising costs and parking price elasticities. “High” cruising costs assume the average speed of 14 km h<sup>-1</sup> reported in downtown San Francisco, and translate to a cost per hour of \$1.98; in this case, cruising vehicles make no attempt to seek out congested traffic. “Low” cruising costs are based on the “possible gridlock” constraint discussed above, and translate to a speed of 0.5 km h<sup>-1</sup> and a cost per hour of \$0.29. The

parking price elasticities span the range of  $-0.20$  to  $-0.38$  reported in downtown San Francisco studies (Vaca & Kuzmyak 2005, p. 13-7). The estimates in Table 4 include both the effect of excess travel (the right-hand column in Table 2), and the effect of reduced parking costs.

The estimates in the sensitivity tests vary considerably based on different parking price elasticities, although in all cases the impact on vehicle travel is substantial. Interestingly, different assumptions for cruising costs have little impact on total vehicle travel estimates. Under the “high” cruising cost scenario, fewer vehicles (6%) cruise, but they mostly shift to free on-street parking instead. The average parking cost per trip (\$0.69) is still substantially lower than current parking costs, and vehicles traveling to free on-street parking travel further than those that are cruising. However, congestion would be substantially reduced under this high cruising cost scenario. Under the “low” cruising cost scenario, almost half of vehicles (48%) cruise, but they drive so slowly that they generate little excess travel in the process.

The ultimate outcome will necessarily be different from the results presented here. The analysis does not attempt to capture the market dynamics through which parking prices and employer parking subsidies will respond to the future behavior of AVs. Nor does the analysis consider the physical roadway constraints to increased vehicle travel (although many of these will diminish due to the capacity-enhancing effects of AVs); the second-order effects on mode choice and route choice of other travelers; or the likely policy and regulatory responses of cities and state governments. Rather than a prediction, the analysis here should be interpreted as an illustration of the magnitude and likely direction of AV impacts, which in turn can inform the policy responses discussed in the remainder of this paper.

**Table 4      Sensitivity Analysis of Increased Vehicle Travel**

<i>Price elasticity</i>	<i>Cruising Costs</i>		
	Low	Medium	High
-0.20	62%	65%	72%
-0.30	102%	106%	112%
-0.38	142%	145%	152%

*Cells indicates percentage increase in vehicle travel under each analysis*

## The imperative for congestion pricing

A future where AVs primarily consist of automated taxis – a “shared mobility” model – rather than being individually owned, would partially mitigate the parking challenges identified in this paper. However, the extent to which shared mobility replaces private cars depends as much on consumer preferences and behavioral responses as on public policy; there is no automatic path towards a shared-vehicle future (Sperling 2018). Moreover, the peaked nature of travel demand means that many vehicles will be idle during the middle of the day if a fleet is sized for the morning and afternoon journey-to-work peaks. A cost-minimizing fleet owner would likely instruct them to cruise or seek out free on-street parking. And the simulation presented in this paper suggests that only a small fraction of vehicles (15% or less) need to cruise for parking in order to self-create gridlock.

An initial policy response would be for cities to eliminate unpriced on-street parking (including two-hour free periods and similar rate structures) and set parking prices to achieve a minimum level of availability (Shoup 2005). Indeed, many of the parking reforms warranted by AVs, such as the elimination of minimum parking requirements, are justified today under current technologies (Guerra & Morris 2018). However, parking price changes would do nothing to deter other socially detrimental responses by AVs, particularly cruising and returning home.

Cities could provide free or subsidized peripheral parking close to the city center, setting the hourly price at or below the cost of cruising on city streets—analogueous to the free cellphone lots created at many airports to alleviate cruising at terminals (Kramer & Mandel 2015). However, this approach would further reduce the cost of parking to AVs, in turn encouraging more trips to be made by car. Moreover, the subsidies required for such peripheral lots would need to be large in order to keep the cost below the \$0.48 per hour cost of cruising. While land may be cheaper and more readily available further from the city center, more remote sites would reduce the incentive for AVs to use it.

Could cruising be regulated? After all, prohibitions on cruising, targeted against teenagers and gay men, have long existed in US cities such as Los Angeles, where on certain streets a driver may not pass a control point more than once in a given period. AVs, however, do not need to cruise in a circle, but instead could follow each other in a complicated pattern of slow-moving traffic. It would also be difficult to discern intent—for example, distinguishing an AV that is cruising from one that is carrying out a legitimate errand, or relocating.

Instead, a simpler and more economically attractive policy response is congestion pricing—long advocated by economists and urban policy makers as the optimum approach to managing urban transportation (Vickrey 1963; Downs 2004). By setting a fee or tax equal to the congestion, environmental and other externalities from vehicle travel, AVs would internalize the negative consequences of their alternative parking strategies.

Because the ability of AVs to cruise blurs the boundary between parking and travel, congestion pricing programs would need to be designed to avoid a perverse incentive to cruise in order to avoid a parking fee, and to drive slowly to minimize a distance-based fee. This could be achieved by two complementary prices – a time-based charge for occupying the public right-of-way, whether stationary or in motion, and a distance- or energy-based charge that internalizes the other externalities from driving. A surcharge on zero-occupancy vehicles could also reduce the incentive to cruise or return home.

The results presented here can be directly interpreted as the magnitude of the fee that would be necessary to deter cruising. If vehicles can park for \$4 per hour but cruise for \$0.48 per hour, then a charge of \$3.52 per hour would be sufficient to encourage cost-minimizing vehicles to pay for parking. While the optimum fee would depend on a wider range of considerations, including the quantification of external costs, the difference between hourly parking rates and hourly cruising costs provides a first-order approximation of an appropriate time-based charge.

## **Conclusion**

This paper suggests that the parking behavior of autonomous vehicles would land cities with a twofold blow—a dramatic drop in the cost of parking that encourages more trips by car, and greater vehicle travel and congestion from each trip due to cruising, returning home, and traveling to free on-street spaces. The reduced price of parking would likely increase vehicle travel to dense, urban cores by 98%, while cruising and travel to and from remote parking spaces would add a further 8%. Fundamentally, AVs will negate one of the central pillars of Transportation Demand Management programs that seek to reduce vehicle travel in downtowns, university campuses and other employment centers.

Congestion pricing has long been a holy grail for urban policy, but political and technological considerations have hampered its widespread use beyond a small number of cities. AVs provide

both the opportunity and the imperative for its implementation. The opportunity stems from the lack of an existing constituency of AV owners who would immediately pay the fee; any new charge or tax faces less opposition when it affects no one at the time of adoption. The imperative stems from the urban chaos that could result from AVs cruising for parking, and from the elimination of parking pricing as a congestion management policy. Congestion pricing makes economic sense in any urban future, but even more so in a world of autonomous vehicles.

## **Acknowledgements**

Thanks to Kate DoVale for excellent research assistance, to Joe Castiglione and Bhargava Sana for providing outputs from the SF-CHAMP travel demand model, and to Mark Massoud for helpful comments on an earlier draft. I also appreciate feedback from Jonathan Levine, Robert Hampshire and other seminar participants at the University of Michigan, as well as two anonymous reviewers.

## Appendix: Cost of vehicle travel

This appendix provides estimates of the marginal cost of vehicle travel, comprising fuel (gasoline or electricity), as well as maintenance, tires, distance-based depreciation and other costs that increase with the distance traveled. The marginal costs of travel as a function of both time and distance are a key input into the analysis in the main body of the paper.

Costs are estimated for a gasoline-powered internal-combustion vehicle (IC), and a battery-electric vehicle (EV). A point estimate is provided for urban driving conditions, and also an estimate of costs as a function of vehicle speed. U.S. values are used; in most other countries, these costs would be greater due to higher energy and transportation taxes. All costs are expressed in 2018 US dollars.

### Point estimates

#### Internal-combustion vehicle

The baseline estimate of \$0.211 per mile from Barnes and Langworthy (2004) assumes urban driving conditions, an even share of automobiles and light trucks, and a fuel price of \$1.50 per gallon. The \$0.211 estimate is updated as follows (Table A-1), to give a total of \$0.19 km<sup>-1</sup>:

- Gasoline costs were 71% higher in March 2018 (\$2.56, according to EIA<sup>2</sup>) compared to the 2003 baseline.
- Non-gasoline costs are increased by 36.5%, in line with the change in the Consumer Price Index for urban consumers from January 2003 to January 2018.

An alternative estimate (AAA 2017) is provided by AAA, a membership organization for motorists. The AAA figures provide total costs of driving assuming 10,000, 15,000 or 20,000 miles per year, meaning that marginal costs can be calculated as the difference between these totals. The marginal cost per km calculated from AAA is \$0.14 (moving from 10,000 to 15,000 miles per year) or \$0.18 (moving from 15,000 to 20,000 miles per year), based on an average gasoline price of \$2.33 per gallon. When adjusted upwards to account for inflation and higher fuel prices, and converting to costs per km, these two estimates straddle the estimate of \$0.19 km<sup>-1</sup> calculated from Barnes and Langworthy (2004). Therefore, further analysis uses the \$0.19 km<sup>-1</sup> value.

---

<sup>2</sup> [https://www.eia.gov/dnav/pet/pet\\_pri\\_gnd\\_a\\_epmr\\_pte\\_dpgal\\_w.htm](https://www.eia.gov/dnav/pet/pet_pri_gnd_a_epmr_pte_dpgal_w.htm). Gasoline price is for all US, week 3/5/18.



## Battery-electric vehicle

Battery-electric vehicles (EVs) can be more expensive than conventional gasoline cars. However, the extra expense largely accrues at the time of vehicle purchase; marginal costs are typically lower for EVs, given the lower cost of electricity compared to gasoline, and the increased efficiency of EVs.

The US EPA rates the 2018 Nissan Leaf at 30 kWh per 100 miles (net of charging losses). At an average cost of \$0.125 kWh<sup>-1</sup> to US residential consumers, this gives a fuel cost per mile of \$0.0375. Assuming the same non-fuel costs as the gasoline vehicles, this gives a total of \$0.13 km<sup>-1</sup> (Table A-1). Note that this estimate does not include the cost of charging infrastructure.

There is considerable uncertainty in EV costs, particularly regarding how quickly battery costs will fall in the future (Nykvist & Nilsson 2015). However, most estimates suggest that the per-km cost of EVs will be substantially less than internal combustion vehicles. Although the total cost of ownership is more uncertain, EV costs are declining and are lower when they are used more intensively and in urban settings (Palmer et al. 2018). Maintenance costs are also likely to be lower for EVs, due to regenerative braking (which reduces brake pad wear) and an electric drive train (Palmer et al. 2018). Moreover, EVs can take account of discounted nighttime charging rates, meaning that electricity costs may be less than assumed here.

**Table A-1 Marginal costs of vehicle travel**

	IC (based on Barnes & Langworthy, 2004)		EV
	2003 \$	2018 \$	2018 \$
Fuel cost per mile	0.08	0.14	0.04
Non-fuel cost per mile	0.13	0.17	0.17
Total per mile	0.21	0.31	0.21
Total per km	0.13	0.19	0.13

## Speed-dependent estimates

Speed-dependent estimates for IC vehicles are based on real-world measurements of CO<sub>2</sub> emissions from probe vehicles in Southern California, which were fit to a fourth-order polynomial in order to give emissions as a function of speed (Barth & Boriboonsomsin 2008). The resulting estimates of CO<sub>2</sub> are then converted to gallons of gasoline using a standard emissions factor from the U.S. Energy Information Administration. The speed-dependent estimates for EVs are based on real-

world testing measurements of four Nissan Leafs by Idaho National Laboratory (Idaho National Laboratory 2016), increased to account for assumed charging losses of 16%.<sup>3</sup> The same assumptions for electricity costs (\$0.125 kWh<sup>-1</sup>), gasoline costs (\$2.56 gallon<sup>-1</sup>) and non-fuel costs (\$0.17 mile<sup>-1</sup>) are used as in Section 1.1 above.

Table A-2 and Figure A-1 present the results as both costs per kilometer and per hour of travel time. While the marginal costs are lower for EVs at all speeds, the difference is particularly pronounced at low speeds given the ability of EVs to idle at almost zero energy cost, and to take advantage of regenerative braking.

The cost per hour  $c$  for EVs has an almost exactly linear relationship with speed  $s$ , estimated via ordinary least squares as:

$$c = 0.2326 + 0.1233s$$

implying an intercept of \$0.23 hr<sup>-1</sup>, which can be interpreted as the cost of running auxiliary electrical systems, and a cost of \$0.12 hr<sup>-1</sup> for each increment of speed (measured in km hr<sup>-1</sup>).

---

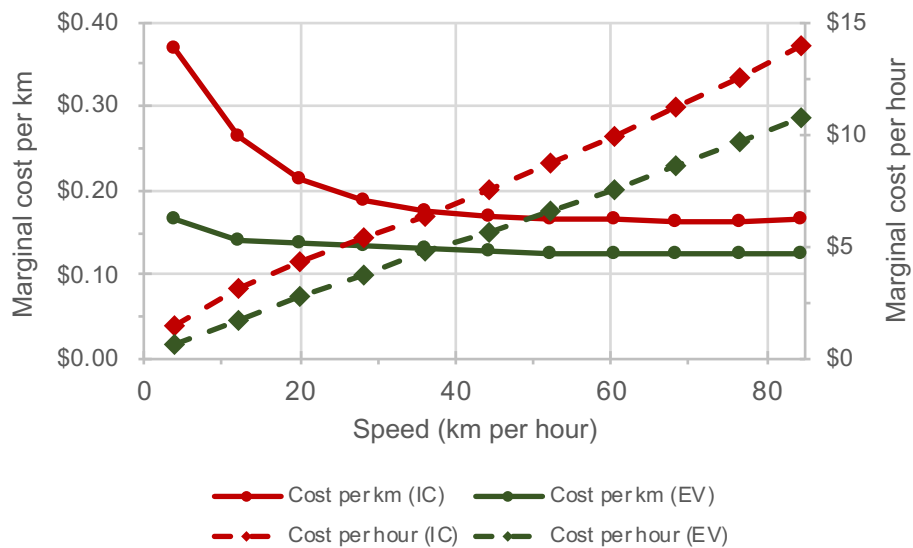
<sup>3</sup> <https://www.fueleconomy.gov/feg/atv-ev.shtml>

**Table A-2 Speed-dependent marginal costs of vehicle travel**

km h <sup>-1</sup>	Internal Combustion (IC)			Battery Electric Vehicle (EV)		
	mpg	cost km <sup>-1</sup>	cost hour <sup>-1</sup>	Wh mile <sup>-1</sup>	cost km <sup>-1</sup>	cost hour <sup>-1</sup>
0						\$0.23*
1						\$0.36*
2	5.2	\$0.41	\$0.83			\$0.48*
4	6.1	\$0.37	\$1.48	660	\$0.17	\$0.67
12	10.2	\$0.26	\$3.17	379	\$0.14	\$1.71
20	14.7	\$0.21	\$4.31	324	\$0.14	\$2.74
28	19.1	\$0.19	\$5.35	306	\$0.13	\$3.79
36	22.6	\$0.18	\$6.41	275	\$0.13	\$4.78
44	25.0	\$0.17	\$7.52	239	\$0.13	\$5.69
52	26.5	\$0.17	\$8.70	212	\$0.13	\$6.59
60	27.3	\$0.16	\$9.94	209	\$0.13	\$7.59
68	27.5	\$0.16	\$11.24	215	\$0.13	\$8.64
76	27.5	\$0.16	\$12.57	218	\$0.13	\$9.68
84	27.3	\$0.16	\$13.92	219	\$0.13	\$10.71

\* Estimated based on linear fit. See text

**Figure A-1 Speed-dependent marginal costs of vehicle travel**



## References

- AAA, 2017. *Your driving costs*, Heathrow, FL. [https://exchange.aaa.com/wp-content/uploads/2017/08/17-0013\\_Your-Driving-Costs-Brochure-2017-FNL-CX-1.pdf](https://exchange.aaa.com/wp-content/uploads/2017/08/17-0013_Your-Driving-Costs-Brochure-2017-FNL-CX-1.pdf).
- Anas, A. & Lindsey, R., 2011. Reducing Urban Road Transportation Externalities: Road Pricing in Theory and in Practice. *Review of Environmental Economics and Policy*, 5(1), pp.66–88. <http://reep.oxfordjournals.org/content/5/1/66.abstract>.
- Anderson, J.M., Kalra, N., Stanley, K.D., Sorensen, P., Samaras, C. & Oluwatola, O.A., 2016. *Autonomous vehicle technology. A guide for policymakers*, Santa Monica: Rand Corporation. [https://www.rand.org/pubs/research\\_reports/RR443-2.html](https://www.rand.org/pubs/research_reports/RR443-2.html).
- Barnes, G. & Langworthy, P., 2004. Per Mile Costs of Operating Automobiles and Trucks. *Transportation Research Record*, 1864(1), pp.71–77.
- Barth, M. & Boriboonsomsin, K., 2008. Real-World Carbon Dioxide Impacts of Traffic Congestion. *Transportation Research Record: Journal of the Transportation Research Board*, 2058, pp.163–171.
- Bragg, D. & Pazzano, S., 2018. *The Transportation Revolution: The impact of ride-hailing and driverless vehicles on real estate*, <http://s3-us-west-2.amazonaws.com/gstqa-us-west/uploads/2017/10/19153037/ULI-Green-Street-Fall-17-Presentation.pdf>.
- Childress, S., Nichols, B., Charlton, B. & Coe, S., 2015. Using an Activity-Based Model to Explore the Potential Impacts of Automated Vehicles. *Transportation Research Record: Journal of the Transportation Research Board*, 2493, pp.99–106.
- Courtney, S., 2018. With Self-Driving Cars on Horizon, Cities Worry About Parking. *Bloomberg Government*. <https://about.bgov.com/blog/self-driving-cars-cities-worry-parking/>.
- Downs, A., 2004. *Still stuck in traffic: coping with peak-hour traffic congestion*, Washington, D.C.: Brookings Institution Press.
- Erickson, A., 2012. A Brief History of the Parking Meter. *CityLab*. <https://www.citylab.com/transportation/2012/04/brief-history-parking-meter/1594/>.
- Fagnant, D.J. & Kockelman, K., 2015. Preparing a nation for autonomous vehicles: opportunities, barriers and policy recommendations. *Transportation Research Part A: Policy and Practice*, 77, pp.167–181. <http://www.sciencedirect.com/science/article/pii/S0965856415000804>.
- Fagnant, D.J. & Kockelman, K.M., 2014. The travel and environmental implications of shared autonomous vehicles, using agent-based model scenarios. *Transportation Research Part C: Emerging Technologies*, 40, pp.1–13. <http://www.sciencedirect.com/science/article/pii/S0968090X13002581>
- Friedrich, B., 2016. The Effect of Autonomous Vehicles on Traffic. In M. Maurer, J. C. Gerdes, B. Lenz, & H. Winner, eds. *Autonomous Driving*. Berlin: Springer Berlin Heidelberg, pp. 317–334. [http://link.springer.com/10.1007/978-3-662-48847-8\\_16](http://link.springer.com/10.1007/978-3-662-48847-8_16).
- Grant, P., 2018. Say Goodbye to Garages as Developers Imagine a Driverless Future. *Wall Street Journal*. <https://www.wsj.com/articles/say-goodbye-to-garages-as-developers-imagine-a-driverless-future-1517317200>.
- Guerra, E. & Morris, E.A., 2018. Cities, Automation, and the Self-parking Elephant in the Room. *Planning Theory and Practice*, 19(2), pp.291–297.

- Harper, C.D., Hendrickson, C.T. & Samaras, C., 2018. Exploring the Economic, Environmental, and Travel Implications of Changes in Parking Choices due to Driverless Vehicles: An Agent-Based Simulation Approach. *Journal of Urban Planning and Development*, 144(4), p.04018043.
- Hess, D., 2001. Effect of Free Parking on Commuter Mode Choice: Evidence from Travel Diary Data. *Transportation Research Record*, 1753(1), pp.35–42.
- Idaho National Laboratory, 2016. On-Road Usage and Performance Summaries.
- Inci, E., 2014. A review of the economics of parking. *Economics of Transportation*, 4(1), pp.50–63.
- Krajzewicz, D., Erdmann, J., Behrisch, M. & Bieker, L., 2012. Recent Development and Applications of SUMO - Simulation of Urban MObility. *International Journal On Advances in Systems and Measurements*, 5(3–4), pp.128–138.
- Kramer, L.S. & Mandel, S., 2015. *Cell Phone Lots at Airports*. ACRP Synthesis 62, Transportation Research Board, Washington, DC.  
[http://onlinepubs.trb.org/Onlinepubs/acrp/acrp\\_syn\\_062.pdf](http://onlinepubs.trb.org/Onlinepubs/acrp/acrp_syn_062.pdf).
- Levinson, D., 2015. Climbing Mount Next: The Effects of Autonomous Vehicles on Society. *Minnesota Journal of Law, Science and Technology*, 16(2), pp.787–809.
- Liu, X., Lai, L., Kong, Y. & Vine, S. Le, 2018. Protected Turning Movements of Noncooperative Automated Vehicles: Geometrics, Trajectories, and Saturation Flow. *Journal of Advanced Transportation*, p.1879518.
- Mahmassani, H.S., 2016. 50th Anniversary Invited Article—Autonomous Vehicles and Connected Vehicle Systems: Flow and Operations Considerations. *Transportation Science*, 50(4), pp.1140–1162. <http://pubsonline.informs.org/doi/10.1287/trsc.2016.0712>.
- Martinez, L.M. & Viegas, J.M., 2017. Assessing the impacts of deploying a shared self-driving urban mobility system: An agent-based model applied to the city of Lisbon, Portugal. *International Journal of Transportation Science and Technology*, 6(1), pp.13–27.
- Maryniak, P., 2018. City may be first to adjust zoning laws for driverless vehicles. *East Valley Tribune*.  
[http://www.eastvalleytribune.com/news/city-may-be-first-to-adjust-zoning-laws-for-driverless/article\\_4a43a342-5250-11e8-92e4-3bf0710e75ca.html](http://www.eastvalleytribune.com/news/city-may-be-first-to-adjust-zoning-laws-for-driverless/article_4a43a342-5250-11e8-92e4-3bf0710e75ca.html).
- Milakis, D., van Arem, B. & van Wee, B., 2017. Policy and society related implications of automated driving: a review of literature and directions for future research. *Journal of Intelligent Transportation Systems*, 21(4), pp.324–348.
- Nourinejad, M., Bahrami, S. & Roorda, M.J., 2018. Designing parking facilities for autonomous vehicles. *Transportation Research Part B: Methodological*, 109, pp.110–127.
- Nykqvist, B. & Nilsson, M., 2015. Rapidly falling costs of battery packs for electric vehicles. *Nature Climate Change*, 5(4), pp.329–332.
- Palmer, K., Tate, J.E., Wadud, Z. & Nellthorp, J., 2018. Total cost of ownership and market share for hybrid and electric vehicles in the UK, US and Japan. *Applied Energy*, 209, pp.108–119.
- Parkopedia, 2017. *Global parking index*,  
[https://www.parkopedia.com/static/reports/global\\_parking\\_index2017-parkopedia.pdf](https://www.parkopedia.com/static/reports/global_parking_index2017-parkopedia.pdf).
- Pratt, R., 2013. *Traveler Response to Transportation System Changes*. TCRP Report 95, Ch. 1, Washington, DC.

- Schlossberg, M., Riggs, B., Millard-Ball, A. & Shay, E., 2018. *Rethinking the Street in an Era of Driverless Cars*, Eugene: Urbanism Next. <https://urbanismnext.uoregon.edu/2018/01/25/new-report-rethinking-the-street-in-an-era-of-driverless-cars/>
- SFMTA, 2014. *San Francisco Parking Census Fact Sheet*, San Francisco. <http://sfpark.org/resources/parking-census-data-context-and-map-april-2014/>.
- SFMTA, 2017. *San Francisco Residential Permit Parking Evaluation and Reform Project*, San Francisco. [https://www.sfmta.com/sites/default/files/reports-and-documents/2017/12/sfmta\\_rpp\\_evaluation\\_reform\\_project\\_2017.pdf](https://www.sfmta.com/sites/default/files/reports-and-documents/2017/12/sfmta_rpp_evaluation_reform_project_2017.pdf).
- Shoup, D.C., 2005. *The high cost of free parking*, Washington, DC: Planners Press.
- Sperling, D., 2018. *Three Revolutions. Steering Automated, Shared, and Electric Vehicles to a Better Future*, Washington, D.C.: Island Press.
- Vaca, E. & Kuzmyak, J.R., 2005. *Parking Pricing and Fees. Traveler Response to Transportation System Changes*. TCRP Report 95, Ch. 13, Washington, DC.
- Verhoef, E., Nijkamp, P. & Rietveld, P., 1995. The economics of regulatory parking policies: The (im)possibilities of parking policies in traffic regulation. *Transportation Research Part A*, 29(2), pp.141–156.
- Vickrey, W.S., 1963. Pricing in urban and suburban transport. *American Economic Review*, 53(2), pp.452–465.
- Wadud, Z., MacKenzie, D. & Leiby, P., 2016. Help or hindrance? The travel, energy and carbon impacts of highly automated vehicles. *Transportation Research Part A: Policy and Practice*, 86, pp.1–18.
- Zakharenko, R., 2016. Self-driving cars will change cities. *Regional Science and Urban Economics*, 61, pp.26–37.
- Zhang, W. & Guhathakurta, S., 2017. Parking Spaces in the Age of Shared Autonomous Vehicles: How Much Parking Will We Need and Where? *Transportation Research Record: Journal of the Transportation Research Board*, 2651, pp.80–91.
- Zhang, W., Guhathakurta, S., Fang, J. & Zhang, G., 2015. Exploring the Impact of Shared Autonomous Vehicles on Urban Parking Demand: An Agent-based Simulation Approach. *Sustainable Cities and Society*, 19, pp.34–45. <http://www.sciencedirect.com/science/article/pii/S221067071530010X>.