Curbing Zombie Cars: Implementing a VMT Tax on Zero-Occupant AVs to Discourage Unnecessary Trips

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INTRODUCTION

Like many American cities, Atlanta experienced an infrastructure boom in the post-war years that resulted in a network of highways and interstates encouraging an automobile-dependent lifestyle for its residents. With no natural boundaries, Atlanta's growth sprawled outward creating suburbs in all directions. Today, Atlanta is home to 4.5 million residents whose primary mode of transportation is the car. The resulting congestion across the metro region costs $1,130 per commuter per year (*1*) and congestion remains high on the list of resident's complaints (*2*). While the advent of automated vehicles ("AVs") is poised to usher in an era of unprecedented road safety among other benefits, it is likely that the technology will lead to unexpected changes in the urban fabric of the city, similarly to the way cars reshaped Atlanta a century ago.

One particularly harmful potential consequence of AVs is the likelihood that private owners will begin to increase the number of trips their vehicles make, because now the vehicle can make trips unsupervised by human drivers. Many owners will value the ability to send a vehicle home unsupervised in order to avoid paying for increasingly expensive parking in the city, but this behavior potentially *doubles* the amount of vehicle-miles traveled ("VMT") accrued. Any increase in VMT is undesirable, but a sharp uptick in peak hour VMT in Atlanta would be gridlock inducing.

AVs are not yet commercially available, so lawmakers have the rare opportunity to take steps to prevent this undesirable behavior before it begins, rather than having to retroactively alter behavior after it has become commonplace. One pre-emptive solution to mitigating unnecessary VMT is to charge empty AVs ("zombie cars") a tax for each mile they drive. If the tax is set high enough, it could deter owners from sending their cars on unnecessary trips, choosing to park instead of accruing additional VMT.

This report sets out the formula that jurisdictions should use to set the rates for owners of internal-combustion engine AVs ("ICE AVs") and owners of electric AVs ("EAVs") and applies these rates to the Atlanta metro area. Upon analysis, the rate should be set to at least $0.14 per mile for ICE AVs and to $0.23 per mile for EAVs in the Atlanta area.

BACKGROUND

Automated vehicles

Automated vehicles (frequently shorted to "AVs" and interchangeable referred to as "autonomous vehicles" or "self-driving cars" or "driverless cars") are a new mode of transportation enabled by advanced computers. Using a suite of cameras, radars, LiDAR, and other sensors, AVs are capable of sensing the environment around them and making decisions on how to proceed based on a pre-determined user input, such as an occupant wanting to be delivered to a particular location.

The Society for Automotive Engineers International (SAE) recognizes six levels of automation for vehicles (some of which are already being sold commercially) as outlined in the SAE International Standard J3016 published in 2014 (*3*). Figure 1 below is SAE's summary chart explaining the six levels of automation. Essentially, Levels 0 through 2 require human drivers to monitor the driving environment, while Levels 3 through 5 allow the automated driving system to monitor the driving environment. While Level 5 personal vehicles are not yet commercially available, models are currently being developed and are estimated to be available to the buying public in the 2020s.

SAE level	Name	Narrative Definition	Execution of Steering and Acceleration/ Deceleration	*Monitoring* of Driving Environment	Fallback Performance of *Dynamic Driving Task*	System Capability *(Driving Modes)*
***Human driver* monitors the driving environment**						
0	No Automation	the full-time performance by the *human driver* of all aspects of the *dynamic driving task*, even when enhanced by warning or intervention systems	Human driver	Human driver	Human driver	n/a
1	Driver Assistance	the *driving mode*-specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	Human driver and system	Human driver	Human driver	Some driving modes
2	Partial Automation	the *driving mode*-specific execution by one or more driver assistance systems of both steering and acceleration/deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	**System**	Human driver	Human driver	Some driving modes
***Automated driving system* ("system") monitors the driving environment**						
3	Conditional Automation	the *driving mode*-specific performance by an *automated driving system* of all aspects of the dynamic driving task with the expectation that the *human driver* will respond appropriately to a *request to intervene*	System	**System**	Human driver	Some driving modes
4	High Automation	the *driving mode*-specific performance by an automated driving system of all aspects of the *dynamic driving task*, even if a *human driver* does not respond appropriately to a *request to intervene*	System	System	**System**	Some driving modes
5	Full Automation	the full-time performance by an *automated driving system* of all aspects of the *dynamic driving task* under all roadway and environmental conditions that can be managed by a *human driver*	System	System	System	**All driving modes**

FIGURE 1. Summary chart of SAE International's Levels of Driving Automation for On-Road Vehicles.

AV developers, their timelines, and their goals

There are dozens of companies vying to be the first company to bring an AV to market. Most producers are developing either Level 4 or Level 5 autonomous vehicles (*4*). Some producers have stated that they intend to introduce AVs to the market in the same manner that conventional cars are sold, via personal ownership by individual owners. Other producers are planning on producing vehicles expressly for ride-sharing applications like Uber and Lyft. Table 1 below summarizes the stated development goals of the most prominent automakers and technology companies working towards AVs (*4*).

In a 2016 study, Lavasani et al. examined the stated development timelines for AV producers and studied the adoption rate of various other disruptive technologies to determine an S-curve model for AV market penetration in the United States (*5*). The researchers estimate that there will be a cumulative 1.3 million AVs sold by 2030 and that the market saturation point for AVs will be reached in approximately 2050 with around a cumulative 85 million AVs being sold.

TABLE 1 Development Timelines of auto manufacturers and technology companies pursuing AVs

Manufacturer	Stated Timeline	Goal Level of Autonomy	Goal Business Model
GM	Est. 2018	Level 5	Ride-sharing
Ford with Argo AI	2021	Level 4	Ride-sharing
Honda with Waymo	2020	Level 4	Personal Ownership
Toyota	2020	Level 4	Ride-sharing
Renault-Nissan with Microsoft	2020	Level 4	Personal Ownership
Renault-Nissan with Microsoft	2025	Level 5	Personal Ownership
Volvo with Uber	2021	Level 4	Personal Ownership
Hyundai	2020	Level 4	Personal Ownership
Hyundai	2030	Level 5	Personal Ownership
Daimler with Uber	Early 2020s	Level 4	Ride-sharing
Fiat-Chrysler with Uber	2021	Level 4	Personal Ownership
BMW with Intel and Mobileye	2021	Level 4	Personal Ownership
Tesla	2017+	Level 5	Personal Ownership

Automated vehicles and VMT

The rapid development of AVs brings the promise of a radically different transportation future. AV proponents claim that driverless cars will increase safety, ease congestion (and therefore decrease emissions), and decrease commute stressors and road rage (*6*). While these positive externalities may come to pass, AVs will undoubtable introduce negative externalities as well.

Currently, many people choose to own and operate personal vehicles because they are much more convenient than other modes of travel. Conventional cars are available to the owner at a moment's notice, can easily store and transport the owner's cumbersome stuff (like kids school and extracurricular gear), and can go almost anywhere at any time. Personally owned AVs will be able to do all of these things and more. AVs will create an even more tolerable ride than conventional cars by allowing the occupants to devote their attention to something other than the ride itself. It is likely that AV owners will likely tolerate a longer ride (in time and distance) than they would if they were actively driving a conventional car (*7*). Additionally, an AV can avoid the cost of paying for parking in high-demand areas simply by dropping of its occupants then driving empty to a free parking location regardless of how far away that free parking location happens to be. The AV can be programmed to return to the owner's location at a pre-determined time to pick the owner up again. This behavior is deemed "looping" and the trips the AV makes while devoid of passengers are referred to as "zombie trips" made by "zombie cars".

Vehicle miles traveled, or VMT, refers to the number of miles a vehicle (or group of vehicles) travels over a given period of time. Because the space on the road network is a finite resource, every additional mile of VMT exerts a marginal social cost that manifests differently under different conditions. For example, the marginal social cost for a "nighttime trip in a hybrid on a lonely stretch of highway" would be much lower than a trip "in a poorly tuned Hummer on a busy street on a smoggy day” (*8*). Generally, as VMT increases in urban areas congestion, delay, emissions, roadway damage, and noise increase as well (*8*).

To illustrate the detrimental effects looping behavior has on VMT, imagine a person who commutes from the suburbs to the CBD for work on a daily basis. The person usually drives from home to work, parks, then drives from work to home (or some other location before going home). If this person owned an AV, they would be able to ride to work while doing something other than driving, perhaps reading or doing their makeup. They would get out of the car at work, let the car drive to the most convenient free parking location, and program the car to return at the end of the day to pick them up again and take them home. Where there once were only two trips (to work, then home), there are now four trips (to work, then to a free parking location, then to work again, then home). If these additional, unnecessary trips become commonplace among a large group of AV owners, VMT will skyrocket causing the marginal social costs of trips to skyrocket as well. Unfortunately, the AV owners won’t care because they aren’t personally affected; only their cars will experience the excess congestion and inconvenience while their owners are somewhere else entirely. Without an appropriate policy intervention, these zombie cars will overrun our roads and wreak havoc on our transportation network.

Pigovian taxes on socially sub-optimal behavior

Economist Arthur Pigou explained that when a producer’s private interest diverges from the social interest, the producer does not have an incentive to either internalize the cost of the social harm or to externalize the cost of the social benefit. In essence, the economically rational producer will always maximize his own private benefit without regard to society’s harm or benefit (*9*). In the case of AVs, owners will seek to maximize their own benefit (avoiding the cost of parking in the CBD, for example), and in so doing, will inflict a great social harm in the form of increased peak-hour VMT and congestion.

A Pigovian tax is a tax designed to internalize the marginal social cost of some negative externality in order to increase social benefits. Congestion charges are a common form of Pigovian tax applied in transportation. Two of the largest-scale congestion charge projects are the Singapore Area License Scheme and the London Congestion Charge.

The Singapore Area Licensing Scheme

The first-ever congestion pricing system was the Singapore Area Licensing Scheme (SALS) established in the 1975. The system was designed to correct the “environmental pollution, deteriorating quality of life in the city center, and congestion on limited urban roads” quickly developing in Singapore (*10*). At this time, several other cities had experimented with encouraging people “to ride public transport or organize car pools,” but these experiments had little success (*10*). Singapore decided to pursue an economic experiment and began requiring that drivers purchase a special supplemental license and display it on all vehicles driven in the designated Restricted Zone during peak hours (*10*). The SALS was updated to the Electronic Road Pricing (ERP) system in 1998.

Singapore’s ERP is a pay-as-you-use system designed to charge drivers when entering the Restricted Zone and when using specific roads inside the Restricted Zone during peak hours. The fee varies depending on vehicle class and level of congestion. Unlike traditional American tolling systems, Singapore’s drivers don’t stop at a tollbooth to pay, but rather have tolls deducted from prepaid cards via overhead gantries. This allows traffic to move through the tolling stations at full speed which further reduces congestion (*11*).

After the implementation of the ERP system, vehicle entries into the Restricted Zone fell by 70%. This correlates with an average speed increase from 19 km/h to 36 km/h and a morning peak traffic volume reduction of 45%. Both of these metrics exceeded the government's best-case scenarios (*12*).

The London Congestion Charge

The London Congestion Charging Scheme (LCCS), while achieving the same goals as the Singapore ERP, is designed significantly differently. The congestion charge went into effect in 2003 and has been maintained to the present (*13*). Whereas Singapore has a charge to enter the Restricted Zone and multiple charging points within the Restricted Zone, London has a fixed daily rate for entering the cordon area just once. Currently, drivers who enter the London charging zone between 7:00 am and 6:00 pm, Monday through Friday, pay £11.50 per day. While this daily rate can be adjusted down for residents and vehicles meeting special requirements, it is applied evenly throughout the charging zone regardless of which roads are used, time spent in the zone, current congestion levels, or re-entry of the zone during the same day (*14*).

After implementing the charge in 2003, the cordon area saw 20,000 fewer vehicles per day, thus dropping the automobile mode share from 12% to 10%. This two-percentage point reduction led to a 37% increase in average speed, a 30% decline in peak period auto delays, and a 50% decline in peak period bus delays (*13*). Clearly, society at large saw benefits from the Pigovian-style tax on driving in London's congested core. Because individual drivers are also members of society, they also received these benefits after paying for them through the congestion charge.

Uses of Revenues from Pigovian Taxes

Both the Singapore and the London systems successfully generate positive net revenues in addition to reducing congestion. In Singapore, annual gross revenue in 2004 was approximately £25 million and operating expenses were approximately £5 million. Therefore, net revenue for the Singapore ERP was approximately £20 million (*12*). In London, the LCCS was expected to generate £118 million in fees and £72 million in fines for a total gross revenue of £190 million in 2005. LCCS operating expenses for the same year were estimated to be £92 million, therefore, the net revenue for the system was estimated to be £98 million for 2005 (*13*).

In both cities, a majority of the net revenue generated is used to build and maintain the public transit systems that shoulder the extra burden of passengers switching away from private cars. In Singapore, a mass rapid transit (MRT) system was built and includes integrated bus, rail, and taxi services (*12*). In London, TfL expanded the bus network by adding additional capacity, decreasing headways, and prioritizing buses along the roads *before* the LCCS went into effect. The expanded transit network was ready to accept the additional passengers well before they arrived (*12*).

VMT Taxes

Another form of Pigovian taxes on road use are VMT taxes, or taxes charged for each mile a vehicle travels. These taxes can be varied across vehicle class, road class, current congestion, vehicle occupancy, or any other trackable feature of the vehicle or the road.

In recent years, the U.S. has seen an increasing interest in charging VMT taxes in order to more accurately capture the true cost of driving (*8*). Currently, roads are paid for through a combination of state and federal gas tax revenues, tag fees, and federal funds. While all drivers contribute to this funding in some way, most do not directly associate these taxes and fees with the cost of actually using the roads (*8*). They view the roads as quasi-public goods and therefore as *free to use*, and since most people already have a car, driving everywhere makes the most financial sense at an individual level. This is a perverse incentive where the nominally free nature of the road network causes demand to spike too high during peak hours resulting intense congestion. Theoretically, a noticeable Pigovian tax on miles traveled should cause drivers to reconsider their trip-taking behavior. If a VMT tax is implemented correctly, some drivers should choose to take alternative modes or choose to avoid taking the trip altogether (*15*). Either of these options will result in decreased regional VMT, and, therefore, decreased congestion.

Oregon's VMT tax pilot project

In 2006, the state of Oregon began a yearlong pilot project to study the feasibility of VMT taxes as a replacement of state gas taxes. The pilot project also considered the trip-taking behavior changes associated with charging an additional congestion fee on a per mile basis. The researchers recruited 299 drivers and two gas stations to participate. Drivers had a variety of different mileage tracking products installed on their vehicles and were instructed to fill up their tanks at the participating gas stations. VMT was recorded at the pump and the drivers were charged an itemized mileage fee in addition to the cost of the gasoline. Some drivers were also charged a congestion charge. At the study's conclusion, Oregon confirmed that concept of VMT taxes is viable and effective. Additionally, the study produced a 22% decline in VMT when drivers were charged an additional fee for driving on congested roads during peak hours (*16*). This VMT decline aligns with the VMT reduction documented in London after the implementation of the congestion charge.

Massachusetts' AV VMT tax proposal

Two lawmakers in the state legislature of Massachusetts recently proposed a bill regulating AV operation in the state that included a provision to charge AVs $0.025 per mile to drive in the state (*17*). This was explicitly labeled a "road user fee" to compensate for the requirement that AVs be zero-emission vehicles and therefore pay no state gas taxes towards road maintenance. Since the stated goal of this policy is to collect a replacement of the gas tax, it is unlikely to generate the same behavioral response as a tax designed to limit VMT. In 2011, Guo et al. at the Mineta Transportation Institute studied the behavioral responses to the 2005-2006 Oregon VMT test (*18*). Guo subjected some drivers to a supplemental charge for driving and found that "charging a noticeably higher fee for driving in congested conditions successfully achieved the goal of inducing households to reduce their VMT in those times and places where congestion is most a problem" (*18*). The researchers also found that drivers subjected to a gas tax replacement system drove "more instead of less because gas became essentially cheaper" (*18*). These households were paying a flat rate based on VMT, but they paid it only once a month, therefore the effect of the payment was disassociated with their actual driving habits.

The Zombie VMT Tax Proposal

Since Donald Shoup's groundbreaking book "The High Cost of Free Parking" was released in 2005, planners and policymakers across the country have been implementing polices to increase the cost of parking in urban areas, or to limit the oversupply of parking by shifting from parking minimums to parking maximums (*19*). While this change is beneficial overall, it complicates the parking situation for AVs. If urban parking is too expensive or inadequate, zombie AVs will drive further to find free or extremely cheap parking. This behavior would increase VMT and increase the marginal social cost of driving in the urban area.

Future planners and policymakers must ensure that the cost of parking is cheaper than the cost of looping, thereby incentivizing the choice to park instead of loop. They can either lower the cost of parking or raise the cost of looping. Lowering the cost of parking does not lead to desirable outcomes for cities, so they should instead raise the cost of looping. One possible way to raise the cost of looping is to charge a Pigovian tax on the VMT accrued while looping. The AV owner will then have to choose between paying to park and paying to loop. If the cost of looping exceeds the cost of parking, the economically rational AV owner will choose to park thereby saving the marginal social cost increases due to unnecessary VMT.

METHODOLOGY

Several papers have attempted to find "optimal" VMT rates to be used for congestion mitigation. In 2005, Small and Perry found that the optimal rate was around $0.15 per mile for both the United States and the United Kingdom (*20*). In 2016, Zhang and Kockelman proposed a rate of $0.52 per mile for polycentric cities like Atlanta (*21*). While congestion mitigation is similar, in essence, to limiting zombie VMT, these rates reflect a policy goal that seeks to change *existing* behavior. The policy objective of a Zombie Tax is to discourage the *future* adoption of a behavior that is not yet technologically feasible.

If implemented before AVs are commercially available for sale, the Zombie Tax is a proactive attempt to limit future negative externalities by limiting the attractiveness of the detrimental behavior. The derivation of the rate must reflect the policy goals of the rate. It is also necessary to derive two different rates (one rate for internal combustion engine AVs ("ICE AVs") and another rate for electric AVs ("EAVs")) because of the different operating costs of the different vehicle types. Below are general derivations for the two rates, then those rate formulas are applied to the Atlanta area and are calibrated for mitigating zombie VMT during the morning peak period. It is possible that the rate would vary by time of day or by level of congestion; the Atlanta derivations are just one example of a practical application of the generally derived rate formula.

General derivation of the Zombie Tax for Internal Combustion Engine AVs

The break-even point between parking and looping is

$$cost\ of\ parking = cost\ of\ looping$$

The ICE AV owner will likely value the break-even point as follows:

$$ct = ab$$

where,

c = cost to park per hour
t = hours spent parked
a = cost to loop per hour
b = hours spent looping

The cost per hour to park (*c*) and the hours spent parked (*t*) are straightforward. The cost per hour to loop (*a*) can be found as follows:

$$a = \frac{f}{m} * s$$

where,

f = fuel cost per gallon
m = average mpg
s = average speed in mph

The hours spent looping (*b*) can be found as follows:

$$b = \frac{d}{s}$$

where,

d = distance in miles covered while looping

Therefore, the cost of looping (*ab*) can be rewritten as

$$ab = \left(\frac{f}{m} * s\right)\left(\frac{d}{s}\right) = \frac{fd}{m}$$

Now, the break-even point can be rewritten as

$$ct = \frac{fd}{m}$$

When faced with the choice to park or loop, the rational ICE AV owner will make the following decisions:

If

$$ct > \frac{fd}{m} \rightarrow loop$$

and if

$$ct < \frac{fd}{m} \rightarrow park$$

To discourage looping, the Zombie Tax should be implemented at a set rate per mile traveled. The new break-even point would be

$$ct = \frac{fd}{m} + vd$$

where,

v = the tax rate per mile in dollars

The rational ICE AV owner would make the following choices

If

$$ct > \frac{fd}{m} + vd \ \rightarrow loop$$

and if

$$ct < \frac{fd}{m} + vd \ \rightarrow park$$

Solving for *v*, the tax rate at which ICE AV owners are indifferent between parking and looping is

$$v = \frac{ct}{d} - \frac{f}{m}$$

In order for a rational ICE AV owner to choose to park instead of loop, the optimal VMT tax rate must be higher than the indifference point, which can be described as

$$v > \frac{ct}{d} - \frac{f}{m}$$

Assume that a given ICE AV owner pays $795 for an annual parking pass at work, works 8 hours per day (for a total of 2000 hours per year), lives 5 miles away, pays $2.50 per gallon of gas and owns a car that gets 20 miles to the gallon.

c = 0.3975
t = 8
d = 10
f = 2.50
m = 20

$$v^1 > \frac{0.3975 * 8}{10} - \frac{2.50}{20} = 0.318 - 0.125 = 0.193$$

In this scenario, any tax rate above $0.193 per mile will cause the ICE AV owner to choose to park instead of loop.

General derivation of the Zombie Tax for Electric Vehicles
The break-even point between parking and looping is

$$cost\ of\ parking = cost\ of\ looping$$

The EAV owner will likely value the break-even point as follows:

$$ct = gd$$

where,

c = cost to park per hour
t = hours spent parked
g = cost to loop per mile
d = miles covered while looping

The cost per hour to park (c) and the hours spent parked (t) are straightforward. The cost per mile to loop (g) can be found as follows:

$$g = \frac{kr}{100}$$

where,

k = cost of 1 kWh of electricity
r = average kWh/100mi. efficiency rating

Therefore, the cost of looping (gd) can be rewritten as

$$gd = \frac{dkr}{100}$$

Now, the break-even point can be rewritten as

$$ct = \frac{dkr}{100}$$

When faced with the choice to park or loop, the rational EAV owner will make the following decisions:

If

$$ct > \frac{dkr}{100} \rightarrow loop$$

and if

$$ct < \frac{dkr}{100} \rightarrow park$$

To discourage looping, the Zombie Tax should be implemented at a set rate per mile traveled. The new cost of looping would be

$$gd = \frac{dkr}{100} + vd$$

where,

v = the tax rate per mile in dollars

The new break-even point would be

$$ct = \frac{dkr}{100} + vd$$

The rational EAV owner would make the following choices

If

$$ct > \frac{dkr}{100} + vd \rightarrow loop$$

and if

$$ct < \frac{dkr}{100} + vd \rightarrow park$$

Solving for *v*, the tax rate at which ICE AV owners are indifferent between parking and looping is

$$v = \frac{ct}{d} - \frac{kr}{100}$$

In order for a rational EAV owner to choose to park instead of loop, the optimal VMT tax rate must be higher than the indifference point, which can be described as

$$v > \frac{ct}{d} - \frac{kr}{100}$$

Assume that a given EAV owner pays $795 for an annual parking pass at work, works 8 hours per day (for a total of 2000 hours per year), lives 5 miles away, pays $0.05 per kWh for electricity, and drives an EV that is rated for 33 kWh/100 mi.

c = 0.3975
t = 8
d = 10
k = $0.05
r = 30

$$v^2 > \frac{0.3975 * 8}{10} - \frac{0.05 * 30}{100} = 0.318 - 0.015 = 0.303$$

In this scenario, any tax rate above $0.303 per mile will cause the EAV owner to choose to park instead of loop.

Derivation of the Zombie Tax for ICE Vehicles for Atlanta

In order to derive the appropriate rate for the city of Atlanta, several sources were used to determine the appropriate values for the five variables required for the calculation of *v*. All values are for 2015.

First, for the cost of parking (*c*), Pringle's 2016 thesis "Parking policies for resurging cities: An Atlanta case study" was consulted (*22*). Pringle gives the average daily cost of parking in the Downtown and Midtown areas (considered to be the CBD for Atlanta) as $11.74 and $8.83 respectively in 2015. These figures were divided by 24 to arrive at an average hourly rate, then averaged together to arrive at an average geographically appropriate rate of about $0.86 per hour. This includes the cost of both hourly lots and monthly lots. Clearly, the actual parking structure encountered by AV owners in the Atlanta area will vary greatly, so the calculation of this particular figure is highly subject to fluctuation based on the underlying assumptions.

Second, for the time spent parked (*t*), it is assumed that the average commuter works 8 hours per day and therefore needs to park their car for 8 hours per day.

Third, for the distance covered while looping (*d*), a 2015 study by the Brookings Metropolitan Policy Program found that the average commute distance for Atlanta was 12.8 miles (*25*). For the Atlanta-specific application, we are finding the appropriate rate to curb zombie cars during the morning peak when the majority of the congestion is due to commuters driving from the suburbs to the central business district. In order for a commuter vehicle to loop, the vehicle must travel those 12.8 miles back to the free parking location (assumed to be home during the morning peak period), then another 12.8 miles to pick up the AV owner at the end of the workday. Therefore, *d* is set equal to the cumulative miles covered on average, or 25.6 for this Atlanta derivation (*25*).

Fourth, for the fuel cost per gallon (*f*), the Bureau of Labor Statistics estimates that the average price of a gallon of gasoline in the Atlanta metro area was $2.316 for 2015 (*23*).

Finally, for the average mpg (*m*), the National Transportation Statistics (NTS) guide for the fourth quarter of 2017 estimates that the average mpg for all vehicles operating in the United States was 17.9 miles per gallon in 2015. While this is a rough estimate when applied to Atlanta, it is difficult to obtain a more accurate estimate for the metro area (*24*).

Applying these values to the generally derived breakeven point, we find that any tax rate above $0.140 per mile should incentivize an ICE AV owner to park instead of loop in Atlanta in 2015.

$c = 0.86$
$t = 8$
$d = 25.6$
$f = 2.316$
$m = 17.9$

$$v^{ATL1} = \frac{0.86 * 8}{25.6} - \frac{2.316}{17.9} = 0.269 - 0.129 = 0.140$$

Derivation of the Zombie Tax for EVs for Atlanta

In order to derive the appropriate rate for the city of Atlanta, several sources were used to determine the appropriate values for the five variables required for the calculation of *v*. All values are for 2015.

First, for the cost of parking (*c*), Pringle's 2016 thesis "Parking policies for resurging cities: An Atlanta case study" was consulted (*22*). Pringle gives the average daily cost of parking in the Downtown and Midtown areas (considered to be the CBD for Atlanta) as $11.74 and $8.83 respectively in 2015. These figures were divided by 24 to arrive at an average hourly rate, then averaged together to arrive at an average geographically appropriate rate of about $0.86 per hour. This includes the cost of both hourly lots and monthly lots. Clearly, the actual parking structure encountered by AV owners in the Atlanta area will vary greatly, so the calculation of this particular figure is highly subject to fluctuation based on the underlying assumptions.

Second, for the time spent parked (*t*), it is assumed that the average commuter works 8 hours per day and therefore needs to park their car for 8 hours per day.

Third, for the distance covered while looping (*d*), a 2015 study by the Brookings Metropolitan Policy Program found that the average commute distance for Atlanta was 12.8 miles (*25*). For the Atlanta-specific application, we are finding the appropriate rate to curb zombie cars during the morning peak when the majority of the congestion is due to commuters driving from the suburbs to the central business district. In order for a commuter vehicle to loop, the vehicle must travel those 12.8 miles back to the free parking location (assumed to be home during the morning peak period), then another 12.8 miles to pick up the AV owner at the end of the workday. Therefore, *d* is set equal to the cumulative miles covered on average, or 25.6 for this Atlanta derivation (*25*).

Fourth, for the electricity cost per kWh (*k*), the Bureau of Labor Statistics estimates that the average electricity cost in the Atlanta metro area was $0.125 per kWh for 2015 (*23*).

Finally, for the average kWh/100mi. efficiency rating of EVs (*r*), the U.S. Department of Energy estimated that the average electric vehicle used 33 kWh per 100 miles of travel in 2015 (*26*).

Applying these values to the generally derived breakeven point, we find that any tax rate above $0.228 per mile should incentivize an EAV owner to park instead of loop in Atlanta in 2015.

$c = 0.86$
$t = 8$
$d = 25.6$
$k = 0.125$
$r = 33$

$$v^{ATL2} = \frac{0.86 * 8}{25.6} - \frac{0.125 * 33}{100} = 0.269 - 0.041 = 0.228$$

Assumptions for the Atlanta Case Study

While the equation for valuing whether to park or loop is simple, it is made so by several assumptions. First, the equation assumes that the driver is making the decision to park or loop *not circle*. Circling is an already familiar premise; when the time spent at one's destination is short, it is often more beneficial for the driver to circle the block while waiting for the trip to conclude (perhaps, a passenger has gone into a building to drop off something and will be back quickly).

With the assistance of AVs, there will be no drivers or passengers, merely occupants, so a person who is the solo occupant can now program their AV to circle the block while they run inside to complete the errand.

An extension of the first assumption forms the second assumption: that the length of time spent at the destination is known. This is fairly common for a person going to work, and work trips are often the purpose of a majority of trips made during peak hours. Most people travel to work, stay for several hours then leave work to complete other trips and eventually to return home. Therefore, the hours spent parked (t) is usually a known variable. There are mathematical techniques to capture the uncertainty in t, but those techniques are not employed here.

A large exception to this logic is shared on-demand vehicles, provided by services like Uber and Lyft. The behavior of these vehicles is not considered in the derivation of the Zombie Tax, because the behavior is largely unknown. Transportation Network Companies are notoriously reticent about sharing their data. While it might be necessary to subset *autonomous* Ubers and Lyfts when deriving the appropriate rate for the Zombie Tax, it is impossible to do so here because the data is lacking.

As for the politics of implementing the rate, each jurisdiction (perhaps state or metropolitan regions) should derive their own rate suitable to the conditions in the area. Second, the rate should be constructed to affect as many AV owners as possible in order to fully capture the benefits of the Pigovian tax. In Atlanta, peak congestion during weekdays usually occurs during morning and evening rush hours when hundreds of thousands of commuters converge inside the Perimeter for work during the day, then return to the suburbs at night. For Atlanta, it is appropriate to derive the Zombie Tax rate in a way that will affect the behavior of daily commuters.

FINDINGS

Based on the derivation above, a Zombie Tax of at least \$0.14 per mile should be implemented on ICE AVs and a Zombie Tax of at least \$0.23 per mile should be implemented on EAVs in Atlanta to incentivize parking and disincentivize looping behavior by the average commuter. While backed by academic theory, this rate is highly dependent on the assumptions and policy goals underlying it.

Revenue Implications of a Zombie Tax

Table 2 below gives the assumptions for the Atlanta region in 2020. These figures are from the Atlanta Regional Commission's activity-based travel demand model for the AM peak period for 2020 (*27*). Those trips in the "SOV Free" column are trips that occur in exclusively general purpose lanes. Those trips in the "SOV Paid-Elig" column are trips that occur at least in some portion in a paid-access lane, like the interstate HOT lanes.

TABLE 2 Assumptions for the travel during the AM Peak Period for 2020 in Atlanta

	SOV Free	SOV Paid-Elig	SOV Total
Daily Trips	2,585,833.0	56,927.0	2,642,760.0
Avg Travel Time per Trip	25.1	49.4	
Avg Distance per Trip	9.0	24.5	
Total VMT for all Trips	23,272,497.0	1,394,711.5	24,667,208.5
Avg VMT per Trip for all SOV			9.3
1% Total Daily VMT	232,725.0	13,947.1	246,672.1
Half of 1% Total Daily VMT	116,362.5	6,973.6	123,336.0
Qtr. of 1% of Total Daily VMT	58,181.2	3,486.8	61,668.0
1% of Daily Trips	25,858.3	569.3	26,427.6
Half of 1% Daily Trips	12,929.2	284.6	13,213.8
Qtr. Of 1% of Daily Trips	6,464.6	142.3	6,606.9

Table 3 below gives the forecasted revenue under the proposed Zombie Tax plan of $0.14 per mile for ICE AVs and of $0.23 per mile for EAVs, assuming that 1% of total SOV trips are made by AV in 2020, and assuming that 50% of those AV trips choose to loop, and assuming that 50% of those looping trips are made by ICE AVs and the other 50% of those looping trips are made by EAVs.

TABLE 3 Forecasted Revenue for 2020 for the AM peak period in Atlanta for ICE AVs

	Daily	Weekly	Annual
Zombie Tax Revenue for ICE AVs	$ 8,633.52	$ 43,167.61	$ 2,072,045.51
Zombie Tax Revenue for EAVs	$ 14,183.64	$ 70,918.22	$ 3,404.074.77
Total Zombie Tax Revenue	**$ 22,817.17**	**$ 114,085.84**	**$ 5,476,120.29**

Table 4 below gives the forecasted combined revenue from AVs that choose to loop (and therefore pay the Zombie Tax) and from AVs that choose to park (and therefore pay the parking costs in the Atlanta CBD). The calculations in Table 4 hold the same assumptions as in Table 3, that 1% of total SOV trips in 2020 are made by AVs, and that 50% of those AV trips choose to loop and the other 50% choose to park.

TABLE 4 Forecasted Combined Revenue for 2020 for the AM peak period in Atlanta

	Daily	Weekly	Annual
Zombie Tax Revenue	$ 22,817.17	$ 114,085.84	$ 5,476,120.29
Parking Revenue	$ 90,910.94	$ 454,554.72	$ 21,818,626.56
Total AV Revenue	**$ 113,728.11**	**$ 568,640.56**	**$ 27,294,746.85**

If the Atlanta region charged a $0.14 per mile Zombie Tax on ICE AVs and a $0.23 per mile Zombie Tax on EAVs in 2020, they could expect to capture 123,336 miles per day, equaling $22,817.17 generated by the tax per day. The ARC's travel demand model assumes that the AM peak period scenario applies five days per week, from Monday to Friday. Therefore, the weekly revenue estimate is the daily estimate multiplied by five, or $114,085.84 per week. To be conservative in the estimate, the annual figure assumes that the weekly behavior will occur for 48 out of the 52 weeks in a year, accounting for holidays and vacations that full-time works usually experience. Therefore, the annual revenue estimate is the weekly estimate multiplied by 48, or $5,476,120.29 per year.

In short, Atlanta could generate more than $5 million per year from the Zombie Tax and more than $21 million per year from parking fees on AVs if they are proactive in implementing economic policies to guide the growth of AV use in the region.

Public acceptance in general and in Atlanta

A 2011 paper by Sjoquist et al. provides a thorough survey of Atlanta area drivers' stated preferences and anticipated behavioral responses to various alternative revenue generating mechanisms that could be implemented in the state of Georgia. While none of the alternative revenue generating mechanisms directly included a VMT tax on the zombie miles driven by AVs, the theory of VMT taxes was tested, as was an increase in the gas tax, increased parking fees, new toll roads, and managed lanes (*28*).

Sjoquist found that at least a third of all respondents supported the charging of a VMT tax *to all travel*, including travel by conventional, single-occupancy vehicles. This support outweighed support for any level of increase to the gas tax (*28*). It is promising that Georgia residents are open to the idea of VMT taxes; theoretically, they should be even more supportive of a tax that is extremely limited in application.

A briefing paper prepared by the RAND Corporation for the National Surface Transportation Policy and Revenue Study Commission outlined several potential obstacles to successfully implementing a VMT tax in the United States (*16*). Fortunately, most of these obstacles are avoided when the VMT tax is applied in a limited way to only zombie AVs. For example, RAND highlights the need for separate on-board equipment to be installed to monitor location and VMT and determine if the VMT was accrued in a qualifying area (VMT accrued out-of-state should not be eligible for a given state's VMT tax, for example). While this may be true for conventional cars, AVs all come equipped with precise GPS locators because they are necessary for autonomous navigation. Additionally, AV owners have already opted in to their car knowing their precise location at all times and Oregon collected sensitive data without problems, so any potential privacy concerns are assuaged. The RAND study also states that VMT tax would need to be phased in over time to increase public awareness and acceptance. This is not true for a Zombie Tax; if the tax is implemented *before* AVs are commercially available for sale, the tax is just another feature of AV ownership.

CONCLUSION

AV technology promises to usher in a new era of transportation in the modern world. While it is likely that countless lives will be saved to the increased safety capacity of these vehicles, it is also possible that AVs will enable new trip behaviors that could be detrimental to the transportation network. The ability for the AV to drop off its occupants at a destination, then drive itself to a free parking location away from the destination, then return to the destination at a pre-determined time to pick up the occupants is a new behavior deemed "looping." This looping behavior increases the number of trips made and the amount of VMT accrued on the transportation network. If left unchecked, this increased VMT will cause a sharp uptick in the marginal social cost of using the roads until they are in a state of constant congestion. AVs will spend their time trying to access free parking, instead of accessing the available parking nearby.

Planners and policymakers have the rare opportunity to identify these potentially negative externalities and implement proactive policies to ward off the most detrimental effects. A Pigovian-style tax on VMT for so-called "zombie cars" (those operating without any passengers) could help to incentivize parking instead of looping. Two rate formulas were derived above (one formula for ICE AVs and another formula for EAVs) and those formulas were applied to the Atlanta area and calibrated to incentivize parking during a typical AM peak period commute. The appropriate rate for ICE AVs is $0.14 per mile and the appropriate rate for EAVs is $0.23 per mile. If Atlanta were to implement these rates, they could generate over $5 million annually from the Zombie Tax and another $21 million annually from AVs that choose to park instead of drive around. This revenue could be applied to the rest of the transportation network in the region (primarily transit services) to encourage those drivers wishing to switch modes as a result of the increased cost of driving.

As advanced technology enables increasingly convenient behavior, planners and policymakers must harness all the tools at their disposal to encourage the most socially beneficial behavior possible in order to ensure a safe, healthy, and productive environment for all the region's residents.

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