RESEARCH REPORT

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Using Automated Vehicle (AV) Technology to Smooth Traffic Flow and Reduce Greenhouse Gas Emissions

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April 2022

Berkeley Institute of Transportation Studies

Report No.: UC-ITS-2021-26 | DOI: 10.7922/G2JS9NRB

Technical Report Documentation Page

1. Report No. UC-ITS-2021-26	**2. Government Accession No.** N/A	**3. Recipient's Catalog No.** N/A

4. Title and Subtitle Using Automated Vehicle (AV) Technology to Smooth Traffic Flow and Reduce Greenhouse Gas Emissions	**5. Report Date** April 2022
	6. Performing Organization Code ITS Berkeley
7. Author(s) Sulaiman Almatrudi, Kanaad Parvate, Daniel Rothchild, Upadhi Vijay (equal authorship). Prepared by Kathy Jang and Alexandre Bayen	**8. Performing Organization Report No.** N/A
9. Performing Organization Name and Address Institute of Transportation Studies, Berkeley 109 McLaughlin Hall, MC1720 Berkeley, CA 94720-1720	**10. Work Unit No.** N/A
	11. Contract or Grant No. UC-ITS-2021-26
12. Sponsoring Agency Name and Address The University of California Institute of Transportation Studies www.ucits.org	**13. Type of Report and Period Covered** Final Report (June 2020 – December 2021)
	14. Sponsoring Agency Code UC ITS

15. Supplementary Notes

DOI:10.7922/G2JS9NRB

16. Abstract

Passenger and heavy-duty vehicles make up 36% of California's greenhouse gas (GHG) emissions. Reducing emissions from vehicular travel is therefore paramount for any path towards carbon neutrality. Efforts to reduce GHGs by encouraging mode shift or increasing vehicle efficiency are, and will continue to be, a critical part of decarbonizing the transportation sector. Emerging technologies are creating an opportunity to reduce GHGs. Human driving behaviors in congested traffic have been shown to create stop-and-go waves. When waves form, cars periodically slow down (sometimes to a stop) and then speed back up again; this repeated braking and accelerating leads to higher fuel consumption, and correspondingly increasingly GHG emissions. Flow smoothing, or the use of a specially designed adaptive cruise controllers to dissipate these waves, can reduce fuel consumption of all the cars on the road. By keeping all vehicles at a constant speed, flow smoothing can minimize system-wide GHG emissions. This report presents the results of flow-smoothing when used in simulation, discusses current work on implementing flow-smoothing in real world-highways, and presents policy discussions on how to support flow smoothing.

17. Key Words Greenhouse gases, traffic flow, traffic congestion, autonomous intelligent cruise control, intelligent vehicles, fuel consumption, traffic simulation	**18. Distribution Statement** No restrictions.

19. Security Classification (of this report) Unclassified	**20. Security Classification (of this page)** Unclassified	**21. No. of Pages** 34	**21. Price** N/A

Form Dot F 1700.7 (8-72) Reproduction of completed page authorized

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Acknowledgments

This study was made possible with funding received by the University of California Institute of Transportation Studies from the State of California through the Public Transportation Account and the Road Repair and Accountability Act of 2017 (Senate Bill 1). The authors would like to thank the State of California for its support of university-based research, and especially for the funding received for this project. The authors would also like to thank Toyota, Argonne National Laboratory, and Vanderbilt University.

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Table of Contents

Table of Contents

List of Tables

List of Figures

Executive Summary

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Passenger and heavy-duty vehicles make up 36 percent of California's greenhouse gas (GHG) emissions. Reducing emissions from vehicular travel is therefore paramount for any path towards carbon neutrality. Efforts to reduce GHGs by encouraging mode shift or increasing vehicle efficiency are, and will continue to be, a critical part of decarbonizing the transportation sector. Emerging automated vehicle technologies are creating an opportunity to reduce GHGs.

Flow Smoothing can Increase Driving Efficiency

Human driving behaviors in congested traffic have been shown to create stop-and-go waves. When waves form, cars periodically slow down (sometimes to a stop) and then speed back up again; this repeated braking and accelerating leads to higher fuel consumption, and correspondingly increasing GHG emissions. Flow smoothing, or the use of specially designed adaptive cruise controllers to dissipate these waves, can reduce fuel consumption of all the cars on the road. By keeping all vehicles at a constant speed, flow smoothing can minimize system-wide GHG emissions.

Incentives for Manufacturers Are Needed to Deploy Flow Smoothing

The private sector has little incentive to deploy flow smoothing since the primary benefit of flow smoothing is realized at the system-level (i.e., all cars on the road consume less fuel). In turn, governmental action is needed to encourage flow smoothing technologies on a large scale. For example, the Safer Affordable Fuel Efficient (SAFE) Vehicles Rule could be modified to provide automakers an incentivize to develop and include flow smoothing in their fleet. This is especially enticing as commercially available Level 2 adaptive cruise control is already available from several manufacturers and can be adapted into a flow smoothing technology.

Specifically, the benefits of flow smoothing technology could be captured as an off-cycle credit of reducing CO2 emissions. Off-cycle credits, as defined by the Environmental Protection Agency, aim to reward auto manufacturers for technologies that reduce CO2 emissions but whose effect may not be captured in the standardized highway fuel economy tests. Flow smoothing reduces CO2 emissions of an entire system but its effect cannot be captured during the driving cycle test of a single vehicle. Changes to the SAFE Vehicles Rule could award credit to auto manufacturers based on the measured impact of flow smoothing across the whole system. To both predict the effect of flow smoothing and assign credit, the traffic microsimulator called SUMO could be used, which includes emissions models that predict fuel economy with and without flow smoothing present.

Sensitivity Analyses Show That Flow Smoothing is Robust Across a Range of Vehicles

In this study, we developed a simulated testbed to evaluate the effect of prototype flow smoothing controllers and measured the effect of deploying different percentages (10%, 20%, 30%) of equipped automated vehicles (AVs) on the average miles per gallon (MPG) of non-AVs in the traffic system. We found that flow smoothing is capable of nearly doubling the average system-wide mileage, from 19 MPG to 36 MPG. Since the artificial intelligence technologies that power flow smoothing are continually improving, we carried out a sensitivity analyses to determine how robust the existing technology is to external factors (e.g., aggressive driving behavior, varying levels of congestion). We developed a model representing different levels of aggressive human driving behavior, and report on the effectiveness of flow smoothing as a function of both the percentage of aggressive drivers on the road (10%, 20%, 30%, 40%, 50%), and the proportion of flow-smoothing automated vehicles. We find that the maximum average fuel economy (36 MPG) achieved without accounting for aggressive drivers drops significantly (to only 26 MPG) when half of all drivers are aggressive.

To measure system-wide CO2 reduction from flow smoothing it is important that the simulation match the distribution of different vehicle classes present in the traffic system being evaluated. In turn, we first analyzed the average vehicle class distribution in California, recreated it in the simulation, and reported flow smoothing effectiveness for each vehicle type. We find that fuel savings are approximately the same across vehicle classes, with the exception of electric vehicles where flow smoothing has less of an effect, likely due to their regenerative braking already resulting in significant energy savings.

In summary, this study represents the first effort to analysis how flow smoothing can be implemented and proposes a policy mechanism through which it can be realized.

Contents

Introduction

Transportation accounts for 28 percent of U.S. greenhouse gas (GHG) emissions, with truck and automobile emissions comprising 80 percent of transportation-related emissions (EPA 2020b). For vehicles with internal combustion engines, the amount of emissions produced are mainly determined by the total vehicle miles traveled (VMT) and the vehicles' fuel economy. Improvements in auto technology and fuel economy regulations have helped to nearly double the U.S. average fuel economy since 1975 (EPA 2020a). The bulk of this rise in fuel economy can be attributed to improvements in vehicle hardware and software that increase the intrinsic efficiency of the vehicle, such as improvements to vehicle aerodynamics, reductions in tire rolling resistance, deployments of intelligent engine management software, and even increases in the efficiency of vehicle climate control systems. Developing and deploying technologies like these continues to be essential for increasing fuel economy. However, especially as new fuel efficiency technologies offer increasingly marginal improvements, we argue that the focus should be not just on building more efficient vehicles, but on operating those vehicles as efficiently as possible in the real world. Specifically, in this report we focus on dissipating so-called "stop-and-go" traffic, where cars traveling on a highway periodically form waves that propagate down the highway, leading cars to constantly accelerate and brake instead of traveling at a constant speed. As a result of this unnecessary acceleration and braking, traffic waves have been shown to increase fuel consumption by as much as 67 percent (Stern et al. 2018).

Flow smoothing is a technique that uses a type of adaptive cruise control to dissipate these traffic waves, reducing the fuel wasted on unnecessary accelerating and braking. If a large enough fraction of vehicles (~5-30%) on the road have a flow-smoothing cruise controller enabled, traffic waves can be dissipated, even in regions of high congestion. Existing empirical evidence shows that flow smoothing can reduce real-world fuel consumption by 40 percent (Stern et al. 2018). We provide corroborating evidence from traffic microsimulations that flow smoothing can effectively dissipate traffic waves on a realistic section of highway. Overall, scientific evidence that flow smoothing can greatly reduce fuel consumption is mounting, and actual trials of flow-smoothing technologies on a real section of highway will begin soon. Given the current status of flow smoothing technologies, in this study we seek to identify and address some of the hurdles that stand in the way of widespread deployment.

In the following chapters, we describe flow smoothing in more detail (Section titled "Understanding Flow Smoothing"), present our experimental results showing the effectiveness of flow smoothing over a range of external factors (Section titled "Experimental Results"), and describe and discuss the two policies under which we hope to deploy flow smoothing (Section titled “Policy Options for Deploying Flow Smoothing”).

Understanding Flow Smoothing

On a given stretch of roadway, the average following distance between cars is determined by the density of vehicles on the road. When demand for the roadway increases, the density increases, and the average following distance decreases commensurately. As a result, traffic is forced to slow down in order to accommodate the shorter following distance. Given human reaction time, the distance required to stop safely behind a braking vehicle increases with increasing speed, so a smaller gap between cars requires cars to be going slower. In an ideal world, all the cars along a congested roadway would consistently travel at the same constant speed; this would minimize accelerating and braking, thereby minimizing emissions. However, constant-speed flow is unstable in practice. As soon as one driver brakes, trailing cars also have to brake to compensate, eventually leading to traffic waves. In a traffic wave, cars speed up too much when there is space ahead of them, and then they are forced to brake once they meet slower traffic. This accelerating and braking phenomenon forms a positive feedback loop, and has been shown to lead to the spontaneous formation of stop-and-go traffic waves.

Flow smoothing is a technique used to smooth out these traffic waves. By accelerating less than a human would in the same situation, automated flow-smoothing vehicles can eliminate waves, leading to reduced emissions from all cars along the same stretch of road. In 2008, researchers empirically showed that stop-and-go traffic waves can form independently without any external triggers, such as a bottleneck, merging traffic, road construction, and other factors. In their study, Sugiyama et al. (2008) asked human drivers to maintain their vehicle at a specific constant velocity on a ring-shaped road. Very quickly, stop-and-go waves formed, with vehicles periodically coming to a halt, and then accelerating too much. Fortunately, automated vehicles (AVs) — even Level 2 AVs1 — have the potential to mitigate this problem. By accelerating less than a human would, an AV can smooth out the traffic wave, leading eventually to free-flowing traffic. More recently, another study reproduced these findings and found that introducing a single AV following a set driving strategy on a ring road could dissipate the traffic waves, resulting in a 40 percent decrease in overall fuel consumption (Stern et al. 2018).

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[1] The Society of Automotive Engineers (SAE) defines six levels of driving automation ranging from 0 (fully manual) to 5 (fully autonomous). Level 2 (Partial Driving Automation) is where the vehicle can control both steering and acceleration/deceleration. This is not considered self-driving because a human sits in the driver's seat and can take control of the car at any time. Examples include Tesla Autopilot and Cadillac Super Cruise systems. https://www.synopsys.com/automotive/autonomous-driving-levels.html

Figure 1 demonstrates this instability on a simple ringed road in simulation, with traffic moving in a counter-clockwise direction. The left panel shows traffic bunching up on the right-hand side as some vehicles hit their brakes. In the right panel the presence of a single flow-smoothing AV (red car), following a simple hand-coded algorithm, is capable of smoothing the traffic waves. On this simple roadway the AV can transform an unstable system, as seen in Figure 2, where the left panel displays the continual acceleration and deceleration of the vehicles on the track and the right hand panel depicts the resulting stable system with the AV helping all vehicles travel at a constant speed. With the addition of an AV, the human drivers no longer have to brake and re-accelerate, thereby minimizing emissions. Though this simplistic example may break down on more complex and realistic roadways, we can use it to design a system that captures most of the key characteristics of a more effective flow smoothing system.

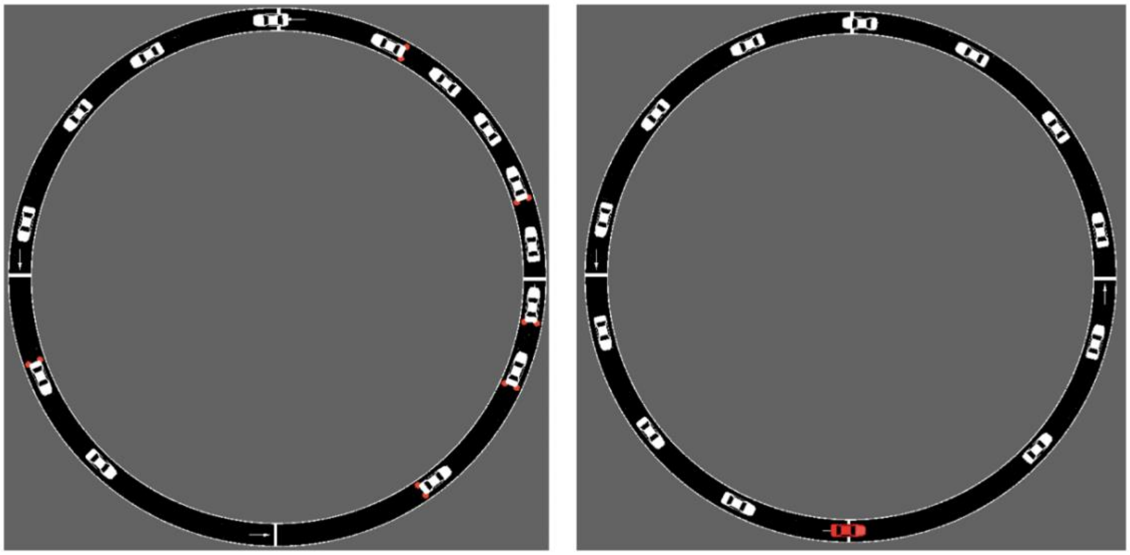

Figure 1: Left: Baseline ring without flow smoothing. Note the bunched vehicles on the right. Right: Ring with red flow smoothing AV. Note the gap opened in front of the AV (red car). Traffic flows counter-clockwise.

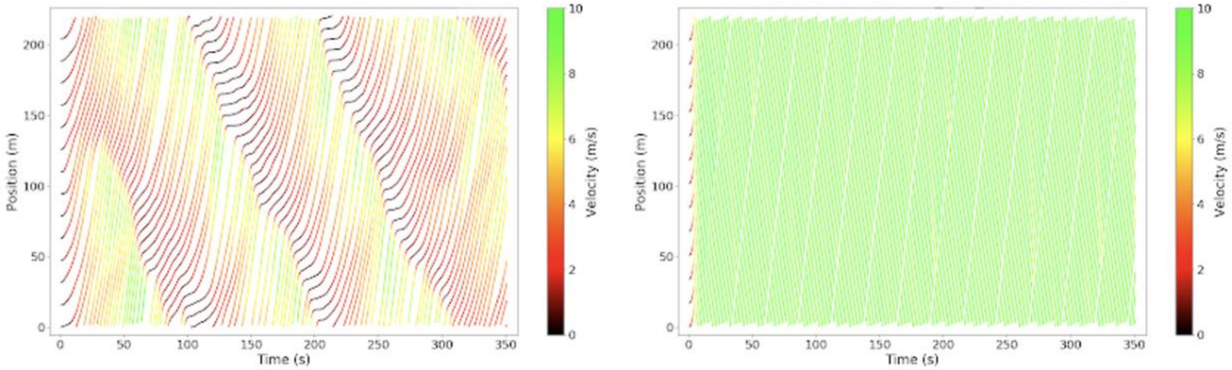

Figure 2: Left: Time-Space diagram for unstable system. Right: Time-Space diagram for stable system

Flow smoothing has already been demonstrated to smooth traffic in a traffic micro-simulator called SUMO (Krajzewicz et al. 2012), which simulates the movements of individual cars along a road network. Other realistic simulations of flow smoothing include a grid road network, a merge lane scenario, and a simulation of the entire Bay Bridge (Wu et al. 2017). Motivated by these successes, ITS-Berkeley expects to be involved in on-road trials of 100 flow-smoothing vehicles as part of a project called CIRCLES that was recently funded by the U.S. Department of Energy. CIRCLES stands for Congestion Impact Reduction via CAV-in-the-loop Lagrangian Energy Smoothing. If the tests are successful, flow smoothing could be deployed on a larger scale as it requires only Level 2 autonomy, which is already present in many commercially sold cars today.

Experimental Results

The existing literature on flow smoothing, while compelling, does not report the types of experimental results needed to deploy flow smoothing. In particular, existing results tend to be presented as changes in average speed or vehicle density (Wu et al., 2017), whereas policy makers are more interested in fuel savings or GHG reductions, or in induced travel demand from less congestion. In addition, policy makers will require that flow-smoothing deployments be effective over a range of scenarios, not just one.

We aim to bridge the gap between the results presented by the research community and the results required for effective policy making. Specifically, in this study we measured the effectiveness of flow smoothing in terms of the improvements in system-wide fuel economy.

In order to approve the use of flow smoothing, regulators need to be confident that flow smoothing will be effective at reducing GHG emissions across a wide variety of situations. For example, regulators need to know how many flow smoothing vehicles must be deployed in order for traffic waves to be effectively smoothed. Another concern is that human drivers may have a more aggressive driving style than is currently modeled in traffic microsimulators, or that human drivers may have different driving styles in different areas, which could reduce the effectiveness of flow smoothing. A last concern is that flow smoothing may be less effective if the surrounding vehicles are already very fuel efficient so that little additional benefit would be attained. In the following two sections, we address each of these concerns using sensitivity analyses.

We present these experiments as a blueprint for the types of data needed for policy-making decisions and hope that future studies using more sophisticated controllers, better calibrated networks, and more realistic human driving behavior will increase the accuracy of these results.

Experimental Setup

We chose a nearly half mile segment of the I-210 highway in Los Angeles to serve as a test bed for evaluating a flow smoothing controller. Specifically, we chose to analyze the FollowerStopper controller, designed by the authors of Stern et al. (2018). This controller aims to maintain a pre-tuned target speed, even if a larger gap opens up in front of the vehicle. In the event a gap does open up, the controller uses the headway in front as a damper to reduce wave instability. Though simple, this controller captures many of the important characteristics of flow smoothing controllers, namely, maintaining a large headway in front of the flow smoothing vehicle and periods of time in which the flow smoothing vehicle is travelling slower than its neighbors.

Using a calibrated model of the I-210 provided by the CIRCLES team, we simulated about five minutes of traffic flow across the highway using SUMO. Initially, the simulation starts with free-flowing traffic. We observe this traffic with FollowerStopper-controlled vehicles inserted at various penetration rates.

Emissions Modeling

Automobiles emit many pollutants, but in this report, we focus only on greenhouse gas emissions. We further restrict our focus to tailpipe emissions (or the carbon intensity of electricity for electric vehicles), since other automotive sources of GHG emissions, such as refrigerant leakages, are insensitive to flow smoothing. The environmental effects of methane emissions from vehicles are negligible, so we focus only on carbon dioxide emissions (Nam et al. 2004). If gasoline always underwent complete combustion, it would be easy to measure the CO2 emissions of a vehicle with high accuracy as simply the stoichiometric equivalent to the fuel consumed. Incomplete combustion and unburned fuel do reduce CO2 emissions, increasing CO and hydrocarbon emissions, respectively. However, the EPA estimates that CO and hydrocarbons account for a much smaller fraction (by mass) of vehicle emissions than CO2, so estimating CO2 emissions stoichiometrically will introduce only a small percentage error (EPA, 2000).

Throughout this report, we therefore use fuel economy as a proxy for CO2 emissions. This metric has the advantage of being more intuitive for drivers, and it can be easily converted to a dollar amount saved on fuel. In addition, for gasoline vehicles, using fuel economy makes results more generalizable, since it assumes nothing about the carbon intensity of fuel production. Optimizing fuel economy itself will not necessarily reduce pollution; internal combustion engines can generally achieve higher fuel economy by running less fuel-rich, at the cost of decreasing the efficiency of catalytic converters, thereby increasing emissions (Watson 1988). However, fuel economy is a useful metric for evaluating how much flow smoothing can alter driver behavior and in turn decrease emissions. For electric vehicles, we report equivalent miles per gallon (MPG) reflective of the average GHG emissions from California’s electric grid. Specifically, we convert the electricity consumed by the vehicle to carbon dioxide equivalents based on statewide average carbon intensity of electricity, and then use the stoichiometric equivalent amount of fuel to arrive at an equivalent measure of MPG.

To estimate fuel economy, we use vehicle models contained within SUMO. SUMO has two emission and fuel consumption models, the Passenger Car and Heavy-Duty Emission Model (PHEM), and a model based on the Handbook of Emission Factors for Road Transport (HBEFA). Both models are based on European Union Standards (EUS). The HBEFA model has the advantage of being empirically calibrated for each vehicle class (Hausberger, 2017). The HBEFA model has also been shown to provide more stable results than PHEM on different SUMO simulation setups (Behrisch and Erdmann 2015). Each simulated vehicle is a assigned to a vehicle class, which is associated with a specific model of how much fuel that type of vehicle burns as a function of factors such as velocity, acceleration and road grade. In our simulations, we used these models to compute the average MPG achieved by the simulated vehicles. We chose seven vehicle classes to represent the vehicles on the road in California, which we grouped into five categories in our simulations:

- EU3, EU4 and EU5, defined as passenger vehicle classes based on their respective EUS-enforced standards for all new registrations in 2001, 2007 and 2011 respectively (AA 2017);
- Average light duty vehicle (LDV) vehicle class based on EUS for vehicles with a gross vehicle weight of ≤ 3.5 tons;
- Average heavy-duty vehicle (HDV) vehicle class based on EUS for vehicles with a gross vehicle weight of ≥ 3.5 tons;
- Passenger alternative fuel vehicle (ALT); and
- Zero emission vehicle (ZEV) vehicles.

For electric vehicles, we converted the energy consumption to an effective MPG by applying the method presented by National Resources Canada (NRC 2014) and using the 2018 California electricity profile provided by the Energy Information Administration (EIA) (EIA 2020). To determine the percentage of each model in the vehicle fleet, we used 2018 registration data from the California Department of Motor Vehicles (DMV) and the Federal Highway Administration (FHWA), and 2019 sales data from the California New Car Dealers Association (CNCDA) (DMV 2018; FHWA 2018; CNCDA 2020). These data include information on each vehicle model which we use to match vehicles to EUS classes as suggested by the International Council on Clean Transport (ICCT) (Blumberg 2015). Figure 3 shows the estimated actual on-road fleet composition and the percentages used in our SUMO simulation models (PHEM and HBEFA). A limitation of this work is that the vehicle classes currently supported by SUMO are based on EUS, rather than U.S. standards. However, as we demonstrate in Figure 6, the benefits of flow smoothing are mostly insensitive to the vehicle classes used.

Effectiveness of Flow Smoothing

We find that deploying flow smoothing vehicles onto the I-210 yields savings in both driving time and fuel usage. Figure 4 shows the time it took two randomly-selected vehicles to complete the course and the amount of fuel consumed in two different scenarios: a baseline scenario without flow smoothing (in red), and a scenario with flow smoothing vehicles present (in blue). Notably, the vehicle in the flow smoothing scenario traversed the stretch of highway in less time, as it did not have to pass through the traffic wave and slow down. Furthermore, the vehicle used less fuel, as it did not have to decelerate and accelerate through the wave.

To illustrate the effects of flow smoothing in aggregate, Table 1 reports the average MPG of all non-AV simulated cars as a function of the proportion of flow-smoothing AVs on the road. As expected, increasing the percentage of flow smoothing vehicles dramatically increases the average fuel economy of the human-driven vehicles by almost a factor of two (from 19 MPG to 36 MPG with 30% flow-smoothing controller-equipped vehicles). This doubling of fuel economy is broadly in line with the empirical results of Stern et al. (2018), who found that fuel consumption decreased by 40 percent with flow smoothing present.

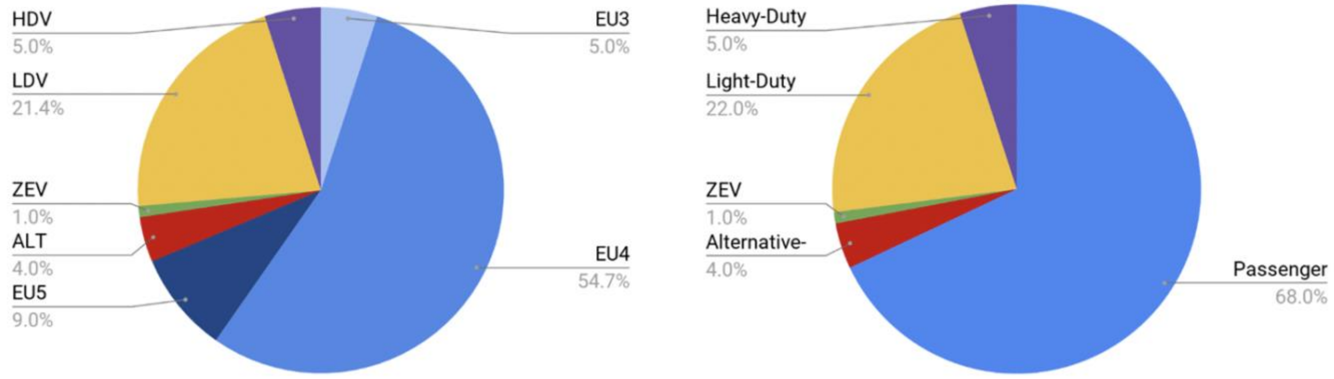

Figure 3: On-road estimated vehicle distribution and simulated vehicle classes. Left: Estimated vehicle distribution. Right: Distribution of simulated vehicle classes.

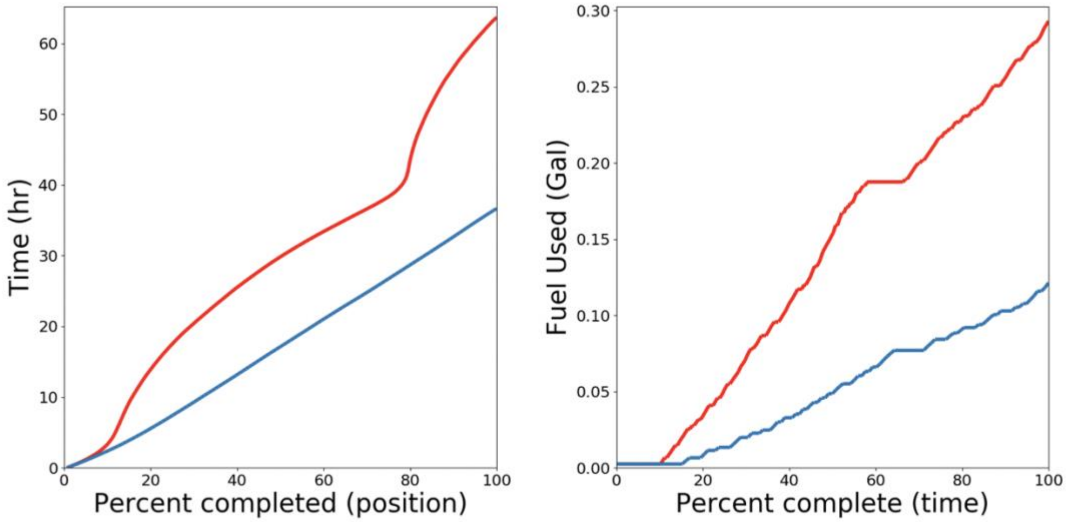

Figure 4: Time and fuel savings for two randomly selected vehicles, in a baseline scenario (in red), and with flow smoothing present (in blue). Left: Space-time plot for two vehicles. Note the waves the red vehicle passes through 60% of the way through. Right: Fuel usage plot for two vehicles.

Table 1: Fuel economy achieved by the simulated human drivers as a function of the proportion of flow-smoothing AVs.

Proportion of Flowing-smoothing AVs	0%	10%	20%	30%
MPG	19 ± 2	25 ± 2	34 ± 4	36 ± 0

Sensitivity Analyses

In this section, we present the results of sensitivity analyses to help understand the uncertainty in our emissions modeling results above. One large source of uncertainty in our calculations is that the simulated human drivers in SUMO may be unrealistic. To better understand the uncertainty of how real human drivers will respond to flow-smoothing vehicles, we introduce more aggressive simulated human drivers, and report how GHG savings are affected by these aggressive drivers.

Another source of uncertainty in our emissions modeling results is that the vehicles we simulated do not accurately reflect vehicles on the road in California today. To understand how varying the distribution of vehicle types affects our emissions modeling results, we performed a sensitivity analysis over vehicle type distribution.

Sensitivity to Aggressive Human Drivers

The validity of an analysis of flow smoothing in a simulated environment is limited by the realism of the human driving models. There are a number of potential mismatches between realistic human driving behavior and the models used in SUMO; we chose to analyze the effect of increasing the aggressiveness of human drivers when making lane changes. Because flow smoothing controllers aim to open large headways as a method of damping waves, we suspected that vehicles change lanes more frequently and into smaller gaps may reduce the effectiveness of the flow smoothing controller.

We designed an "aggressive" human driver model with the same car-following controller as the other humans in the simulation but with a lane changing controller that causes the vehicle to change lanes into smaller gaps between vehicles than the baseline controller would. We then ran experiments to measure the MPG of the non-AVs as above, varying the percentage of flow smoothing vehicles and aggressive drivers. Figure 5 shows the results from this two-dimensional sensitivity analysis. The error bars represent one standard deviation around the mean MPG value obtained over 12 runs with different random speeds. The left-most column of the figure demonstrates the effect of introducing flow smoothing when no aggressive drivers are present. As the human drivers make increasingly aggressive lane changes, the positive effects of flow smoothing are attenuated. With half of the drivers behaving aggressively, the benefits of flow smoothing are almost entirely eliminated.

These results highlight a central challenge of designing flow smoothing controllers: traffic microsimulations have accurate enough human driver models to reproduce large-scale traffic phenomena such as traffic waves, but the effectiveness of flow smoothing also depends on small-scale movements of individual cars (in this case, lane changes). Modeling these minor movements based on real data is a challenging and unsolved problem. To our knowledge, we are the first to examine how the effectiveness of flow smoothing degrades as a function of driver behavior, and we argue that sensitivity analyses like these are crucial for the successful development of flow smoothing controllers. Before we can be confident that flow smoothing microsimulations accurately reflect the effects that flow smoothing would have on a real road, it will be necessary to determine how human drivers actually behave where the system will be deployed, and simulate whether drivers like those will hinder flow smoothers.

For policy makers to be confident about the effectiveness of flow smoothing we suggest they perform additional analyses over a range of possible human driving models in addition to the ones presented in this report.

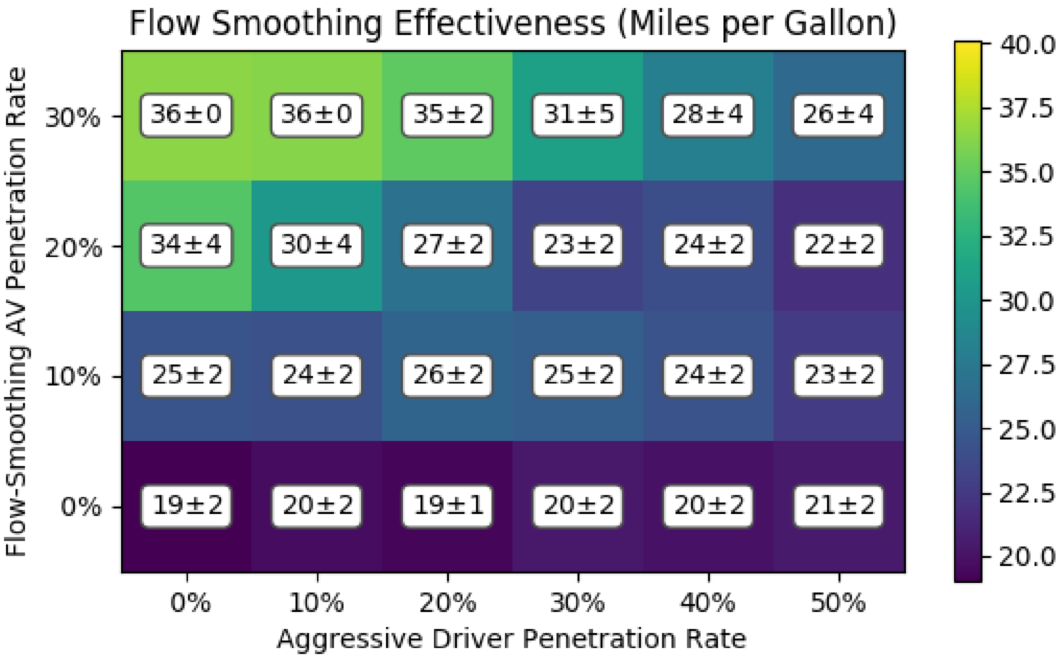

Figure 5: Average fuel economy achieved by simulated human drivers as a function of percentages of flow smoothing vehicles and aggressive drivers. Each cell lists the average and standard deviation of the distribution of MPG obtained when running the simulation with 12 different random seeds.

Sensitivity to Distribution of Vehicle Types

In our emissions model, we assumed an average vehicle class distribution based on the estimated distribution of vehicles on our simulated stretch of highway in Los Angeles. However, such distribution can change significantly in the future with the increase in sales of electric vehicles and possible implementation of tougher standards for energy efficiency in California. To evaluate the sensitivity of the experimental findings to alternative vehicle distributions and to see if the findings hold under different vehicle class distributions, we examined how effective flow smoothing was for each vehicle class in our simulated vehicle population. Figure 6 shows the average improvements in MPG for the different vehicle classes assuming that 30 percent of the vehicles on the road are equipped with flow smoothing controllers. We note that all non-electric passenger vehicles experience about the same doubling in fuel economy due to flow smoothing. Heavy-duty vehicles also experience a significant improvement in MPG but slightly less than that of passenger vehicles and light-duty vehicles. Electric vehicles experience the least improvement, only 25 percent. This is likely due to the prevalence of regenerative braking in electric vehicles, which recaptures energy and thus lessens the negative effects of traffic waves.

Though energy savings are seen for all vehicle types, system CO2 emissions are dependent on the vehicle type mix where flow smoothing vehicles are deployed. As such, matching the simulated distribution to the true distribution is critical for ensuring accurate measurement of CO2 savings.

Potential for Induced Travel Demand

Measuring the potential for induced travel demand caused by improved travel times or higher average speeds is critical when evaluating a flow smoothing system, as it could offset the fuel savings gains generated by flow smoothing vehicles. We therefore present both the system trip time improvement and average speed improvement in Figure 7 to estimate the potential induced demand. In our simulations, we found a nearly 25 percent decrease in trip time and a 50 percent increase in average speeds as the proportion of flow smoothing vehicles increases from zero to 30 percent. In order to estimate the potential for induced demand, we follow Cervero (2003), who comprehensively modeled short- and long-term induced demand effects and concluded that in the long term, “every 10% increase in travel speeds is associated with a 6.4% increase in VMT.” Applying this number directly to flow smoothing is difficult, since the projects used to obtain this elasticity figure were all highway widening projects. Nevertheless, this is likely as accurate an estimate of induced demand as we can feasibly make. In our case, since average travel speeds increase by a maximum of 50 percent, this suggests that we would see an increase in VMT of at most about 30 percent, far less than the doubling in VMT that would be needed to otherwise offset the fuel savings achieved from flow smoothing .

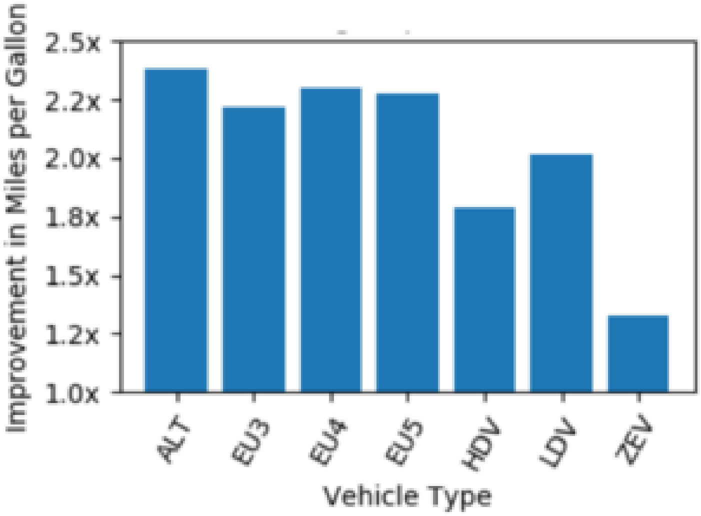

Figure 6: Improvement in fuel economy attributable to flow smoothing for different vehicle types. Flow smoothing is least effective for zero-emissions vehicles due to their regenerative braking.

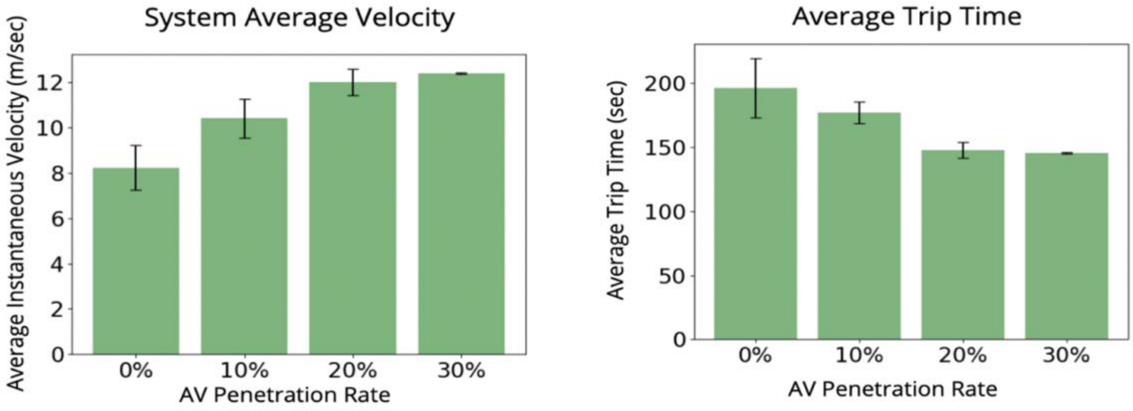

Figure 7: Increase in average trip speeds and decrease in average trips times with flow smoothing. These phenomena suggest that flow smoothing will cause induced demand. Left: Average speed vs. percentage of flow smoothing vehicles. Right: Average trip time vs. percentage of flow smoothing vehicles.

CIRCLES – A Real-World Test Bed

A real-world implementation of flow smoothing is being advanced through the CIRCLES project funded by the U.S. DOE. Spanning three years, the ultimate goal of CIRCLES is to show, through two major real-world tests, that flow-smoothing vehicles improve energy efficiency. This project is being led by UC Berkeley and ITS-Berkeley in partnership with Rutgers University-Camden, University of Arizona, Temple University, Vanderbilt University, and the Tennessee Department of Transportation.

Development for this project began in 2020 by examining the efficacy of flow-smoothing vehicles on simulations of the I-210 highway in Los Angeles, as well as the I-24 highway in Nashville. These simulations yielded a 19 percent improvement in fuel economy on the I-210 with just 6 percent flow-smoothing vehicles. While the simulation results presented in this report indicate that enabling flow smoothing in congestion is promising, the crux of CIRCLES is to examine the results of implementing flow smoothing in the real world. In August 2021, the CIRCLES team tested the efficacy of a flow-smoothing controller developed through reinforcement learning methods for a week on the I-24 highway in Nashville. At the time of writing this report, the data are still being validated. In August 2022, the CIRCLES team will increase the number of flow-smoothing vehicles released in I-24 traffic to 100 vehicles.

To learn more about CIRCLES, please visit: circles-consortium.github.io.

Policy Options for Deploying Flow Smoothing

A main challenge to deploying flow smoothing is that there is little financial incentive for the private sector to do so. Because flow smoothing is an emergent phenomenon, individual vehicle owners don't see any particular benefit by turning on flow smoothing. Rather, collective coordination by a significant number of flow-smoothing vehicles leads to aggregate benefits for the entire roadway. In fact, individual drivers are likely to arrive at their destination slower if they choose to engage flow smoothing, since flow-smoothing controllers work by leaving a gap in front of the controlled vehicle, potentially allowing nearby human drivers room to change lanes and pass.

Because of this effect, we anticipate little financial incentive for auto manufacturers to implement flow smoothing, since consumers primarily benefit from other vehicles using flow smoothing, not from using flow smoothing themselves. We argue that governmental action is needed in order to see flow smoothing widely deployed. Instead of proposing new legislation, we suggest adapting existing policies to encourage flow-smoothing. Since flow smoothing neither makes individual cars or fuels more efficient, or reduce VMT, it does not fall squarely within an existing policy framework; however, below are two potential paths forward for implementing flow smoothing, along with the merits and challenges of each approach.

GHG Mitigation under CEQA

The California Environmental Quality Act (CEQA) establishes a process for state agencies to evaluate and publicly report the anticipated impacts of state-sponsored projects on the environment. As part of the CEQA review process, an agency sponsoring a project (the "lead agency") must prepare an Environmental Impact Report (EIR) for any project that causes significant environmental impacts. The lead agency must also consider methods to mitigate these significant environmental impacts. When deciding which impacts are significant, the lead agency must consider "[t]he extent to which the project may increase or reduce greenhouse gas emissions as compared to the existing environmental setting" (CEQA Guidelines §15064.4). Flow smoothing is a method that reduces GHG emissions, and as such, it could be used as a mitigation method for projects undergoing CEQA reviews. As an example, an EIR for a project to build a new office building might conclude that the additional GHGs emitted by employees commuting to work constitute a significant environmental impact. In this case, the lead agency may propose that flow smoothing be used as a mitigation method; employees could be required to turn on flow smoothing in their vehicles when commuting to work.

Although conceptually straightforward as a policy, implementing flow smoothing as a GHG mitigation method under CEQA is likely to face two main challenges. First, most projects are unlikely to need additional GHG mitigation methods beyond what they already use to satisfy Senate Bill (SB) 743. Under SB 743, CEQA EIRs must quantify the environmental impacts of a project using metrics that "promote the reduction of greenhouse gas emissions, the development of multimodal transportation networks, and a diversity of land uses" (California Public Resources Code §21099(b)(1)). In order to comply with this requirement, lead agencies are likely to use metrics sanctioned by California's Office of Planning and Research (OPR). The OPR published extensive evidence that VMT is a metric that complies with SB 743. The OPR's guidelines establish thresholds beyond which the VMT caused by a project is deemed to be significant, and these thresholds are tightly linked to state-wide GHG reduction targets. As such, any project that mitigates VMT under SB 743 is very likely to have already mitigated any significant increase in GHGs. Flow smoothing could be relevant as a GHG mitigation technique when a project will cause significant GHG emissions due to non-automotive sources. In that case, flow smoothing could be used as a mitigation method if the project had a way to deploy flow smoothing. For example, an industrial complex might produce GHG emissions, and could mitigate that by requiring tenants' employees to use flow smoothing when traveling for work.

The second challenge with using CEQA GHG mitigation as a policy lever is that CEQA allows lead agencies to determine thresholds below which GHG emissions caused by a project are considered insignificant. In particular, agencies are directed to decide if GHG emissions warrant mitigation by checking if "the project emissions exceed a threshold of significance that the lead agency determines applies to the project" (CEQA Guidelines §15064.4 (b) (2)). In order to avoid writing an EIR, or to avoid requiring mitigation methods, lead agencies are incentivized to set lenient thresholds.

In summary, flow smoothing could be deployed as a GHG mitigation method under CEQA if certain conditions are met. However, we suspect that, as written, this policy lever is unlikely to translate to large-scale flow smoothing deployment, since most projects will either already mitigate their GHG emissions with VMT mitigation, or will avoid the need for mitigation by choosing a higher significance threshold for GHGs. In addition, deploying flow smoothing in this way assumes that there is already widespread deployment of a cruise controller that supports flow smoothing, which is not currently the case. The next section considers a policy option that less clearly applies to flow smoothing, but that we believe may be a more fruitful approach overall.

Safer Affordable Fuel Efficient (SAFE) Vehicles Rule

In April of this year, the EPA and the National Highway Traffic Safety Administration released the final SAFE Vehicles Rule, which sets emissions standards for passenger vehicles and light trucks for the next five years. Broadly speaking, SAFE purports to find a balance between increasing road safety and increasing fleet-wide fuel economy. Because flow smoothing has the potential to increase both safety and fuel economy by smoothing the flow of traffic, SAFE seems like a promising policy avenue to encourage the implementation of flow smoothing.

The rule itself sets fleet-wide fuel economy targets that auto manufacturers must meet. Typically, auto manufacturers reach the targets by increasing the fuel economy of the vehicles themselves by, for example, deploying more efficient engine technologies or improving vehicle aerodynamics. Improvements in a vehicle's fuel economy are measured by two standard laboratory test cycles, developed in 1975 (49 U.S.C §32904(c)). Unfortunately, the two-cycle test does not accurately represent all on-road conditions. Recognizing this, the law allows vehicles to demonstrate "off-cycle" emissions reductions for technologies that "have a measurable, demonstrable, and verifiable real-world CO2 reduction that occurs outside the conditions of the Federal Test Procedure and the Highway Fuel Economy Test" (40 CFR §86.1869-12(a)). Manufacturers are increasingly relying on off-cycle credits to achieve the required targets (Lutsey 2018), and we argue that flow smoothing could become another standard technology that grants off-cycle credits to auto manufacturers. There are pre-approved off-cycle credits available (which do not include flow smoothing), but under 40 CFR §86.1869-12(d), "manufacturer[s] may develop an alternative approach" to "measure the emission reduction attributable to an off-cycle technology" if the existing tests proposed by the EPA "insufficiently characteriz[e] the effectiveness of the off-cycle technology." This provision is already used regularly by auto manufacturers to obtain additional off-cycle credits (EPA 2018; 2019a; 2019b). Furthermore, leveraging off-cycle credits in this way in order to deploy intelligent transportation technologies is in fact specifically promoted by the SAFE rule, which states that "manufacturers [should] seek credits [for automated and connected vehicles] through the existing off-cycle credits program where manufacturers would be required to provide data demonstrating direct emissions improvements for the technologies" (SAFE Rule, Federal Register, Vol. 85, No. 84, April 30, 2020, p. 25209).

In summary, we propose policymakers encourage flow smoothing by working with auto manufacturers to apply for off-cycle credits for including flow smoothing in their vehicles. There are two major hurdles to this approach. First, to our knowledge, all existing methods for obtaining credit under SAFE are entirely contained within a single vehicle model: increasing engine efficiency, reducing refrigerant leakage, reducing vehicle mass, and other actions that apply solely to the vehicle being modified. On the other hand, flow smoothing does relatively little to improve the fuel efficiency of an individual vehicle. Instead, if enough flow smoothing vehicles are deployed on a congested roadway, every car traveling on the roadway sees improvements in fuel economy. Although previous emissions-reduction technologies do not operate in this way, the law itself includes no requirement that an emissions reduction technology reduce emissions only from the vehicle on which it is deployed. In fact, the wording of the statute is broadly permissive of any technology that reduces emissions, as long as it has “a measurable, demonstrable, and verifiable real-world CO2 reduction” (40 CFR §86.1869-12(a)). We provide experiments and models below that demonstrate that the benefits of flow-smoothing are indeed “measurable” and “demonstrable.”

The second hurdle is ensuring that the CO2 reductions are “verifiable.” Unlike many existing emissions-reduction technologies, the benefits of flow smoothing cannot be empirically verified in any laboratory test, since they are contingent on human behavior. For one, the drivers of flow-smoothing-enabled vehicles must actually engage flow smoothing when driving in congested traffic. As discussed above, some consumers may be reluctant to do this if they feel the flow smoother is driving slower or less aggressively than they prefer. In addition, flow smoothing may be less effective if the surrounding human drivers drive more aggressively. Instead of verifying emissions reductions through laboratory testing, we propose doing so by collecting data during deployment. Data on how often drivers engage the flow controller can be easily collected, since most vehicles already collect and report large quantities of data to auto manufacturers (Markey 2015).

More difficult is verifying that engaged flow smoothers are actually smoothing traffic, and measuring the quantity of fuel saved. Fortunately, traffic microsimulation is effective at modeling the formation of traffic waves: for a given vehicle density and average velocity, traffic microsimulators can accurately predict what traffic flow would have been like in the absence of flow-smoothing vehicles. With this baseline in hand, the effectiveness of flow smoothing can be measured by sending several (i.e., enough to achieve a low standard error) test vehicles through a congested area, measuring actual fuel consumption, and comparing that to what would have been consumed in the traffic modeled by the microsimulator in the absence of flow-smoothing vehicles. The overall fuel savings due to flow smoothing is then equal to the fuel consumed by the test vehicles (extrapolated to all vehicles on the road) minus the fuel consumed in the microsimulation. This method of measuring the overall fuel savings from flow smoothing has the advantage that it is relatively easy to implement: the required non-flow-smoothed baseline microsimulations only require measurements of traffic velocity and vehicle throughput, which can be easily collected; and the real-world fuel consumption is also straightforward to measure, since it only requires sending a few test vehicles through the road network. One recurring concern is that of induced demand; if flow smoothing causes more vehicles to drive, then the baseline traffic microsimulations will overestimate the magnitude of traffic waves that would be present without flow smoothing. One way to mitigate this problem is to estimate the induced demand that is caused by flow smoothing, and to correct for it when carrying out the baseline microsimulation. We discuss how to estimate induced demand in a previous section.

With the total fuel savings due to flow smoothing in hand, what remains is to divide the credit for reduced fuel consumption among the flow smoothing vehicles. Because manufacturers are collecting the frequency with which its cars actually have flow smoothing turned on, the fuel and GHG savings attributable to flow smoothing can be credited to manufacturers based on the fraction of all active flow-smoothing vehicles belonging to each manufacturer.

While imperfect, we believe this measurement procedure would give a reasonably good estimate of the fuel savings conferred by flow smoothing. It will be necessary to correct for induced demand; early deployments could correct for induced demand using existing models of highway expansion projects, and later deployments should use experience gained from earlier flow smoothing deployments.

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