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Automated Vehicles: Economic Incentives for Environmental Benefits and Safety

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Description of project

Road travel in light-duty vehicles, while of great economic value to private consumers and society, also generates a range of social costs. These include environmental damage from localized and global emissions, energy security concerns from petroleum use, external accident risk, and road congestion. These social costs are addressed only partially by the existing system of fuel taxation and road charges. Research on efficient pricing discusses how taxes might be set on motor fuel and road use to reflect social costs of motor vehicle use. The challenge is to understand how fuel and mileage taxation can alter market outcomes to better manage external costs while taking into account the appropriate level and balance of taxation. Because CAVs can change how people assess their time in vehicles, both in terms of quantity and quality, it is important to design robust policies that can allow the market development of CAVs to take advantage of their private benefits while establishing incentives for beneficial environmental and social outcomes. Our research has two thrusts. First, we make the first known contribution to proposing efficient tax levels for connected autonomous vehicle (CAV) road travel. It extends the existing research for conventional manually-driven vehicles and considers how tax policy may need to change for CAVs given their substantially different societal impacts and private incentives. Our second thrust addresses how consumers will use and adopt CAVs as they become available. We describe our methods and finding for these two thrusts separately but draw conclusions reflecting insights from both.

Methods: Model Structure of an efficient taxation system

To formally model the impact of CAV technology on vehicle use we adapt the representative agent model from Parry and Small (2005).1 We extend their model to account for drivers using manual vehicle (MV) and automated vehicles (AV) $i \in (MV, AV)$, as well as those driving in urban or rural regions j∈(U,R). Additionally, we also account for new versus fleet average vehicles since the on-road fuel economy of new vehicles in later model years (e.g., 2020+) is much higher than the fleet average due to the long lives of vehicles and the increasing stringency of fuel economy regulations.

A representative agent that maximizes utility of consumption, C, miles driven, M, time spent driving, T, and leisure, N, given government payments G, and suffering from pollution, P, and traffic accidents, A. The driver chooses which type of vehicle to drive a CAV or MV, the number of miles driven M, fuel consumption F, expenditures on vehicle (and other financial inputs if road travel) H, and time driving T. The expected accident cost is determined by vehicle choice, CAV or MV, but otherwise exogenous to the private choice, along with pollution damages P.

$$U_{ij} = u(\psi(C_i, M_{ij}, T_{ij}, G), N) - \phi(P_{ij}) - \delta(A_i)$$

where

C_i quantity of a numeraire consumption good, per capita

M_{ij} vehicle-miles of travel

T_{ij} time spent driving

G government spending

N leisure

[1] Parry IWH, Small KA. Does Britain or the United States Have the Right Gasoline Tax? Am. Econ. Rev. 2005;95, No. 4:1276–1289.

P_{ij} quantity of (local and global) pollution
A_i severity-adjusted traffic accidents
L labor supply
I $(1 - T_L)L$, after tax income
F_i fuel consumption
P_F consumer price of fuel equal to the world price plus fuel taxes, $P_W + t_F$
H_i Vehicle and Other driving costs

Private behavior maximizes utility U, taking taxes, congestion, pollution, and accident risk as fixed. Environmental variables are fixed because they are functions of aggregate market behavior, i.e. average fuel-use and VMT $\overline{F}$ and $\overline{M}$, also taken as fixed from the private perspective. This maximization yields the private indirect utility V.

$$V(.) \equiv \&Max \;\; L\big(C_i, F_i, \overline{F}_i, H_i, \overline{M}_{ij}, G, N, L, \mu, \lambda\big)$$
$$= u(\psi(C_i, m(F_i, H_i), \pi(M_i)m(F_i, H_i), G), N) - \phi\left(P_F\left(\overline{F}_i\right) + P_M\left(\overline{M}_i\right)\right)$$
$$- \delta\big(a(\overline{M}_i)\overline{M}_i\big) + \mu\big\{m\big(F_{ij}, H_{ij}\big) - \big(\overline{M}_i\big)\big\} - \lambda\{(1 - t_L)(\overline{L} - N$$
$$- \pi(\overline{M}_i)m(F_{ij}, H_i)) - C_{ij} - (q_F + q_T)F_{ij} - H_i\,\}\,)$$

Social Optimality Conditions
The socially efficient fuel tax is determined by maximizing the private (representative consumer's) indirect utility V with respect to fuel tax rate t_F . Setting this total derivative $\frac{dV}{dt_F}$ to zero yields the first-order necessary condition for the optimum:

$$(\frac{1}{\lambda}\frac{dV}{dt_F} = (E^{P_F} - t_F)(-\frac{dF}{dt_F}) + (E^C + E^A + E\hat{}(P_M))(-\frac{dM}{dt_F}) + t_L\,\frac{dL}{dt_F}$$
$$= 0 \;\; at\ social\ optimum)$$

Efficient Fuel Tax
By setting the marginal net benefit of fuel taxation to zero we can solve for the optimal or efficient fuel tax t_F^*. The same formalism yields the social optimum when the marginal net benefit with respect to fuel tax also accounts for how average (total) travel and fuel use vary with taxation.

Data and Parameters – Optimal Taxation
We parameterize the model focusing on how CAVs are expected to differ from MVs including safety and travel time costs. We also update the model to account for changes in real fuel prices, taxes, costs (damages). Our data (described below) runs in 5 year time steps from 2015 - 2040. Shown are cases that represent fleet Average MVs, New MVs, fleet average CAVs, and new CAVs.

Table 1: Principal Parameters Used in Model

Variable	Units	P&S ($2016)	Ave MV (2015)	New MV (2015)	Ave AV (2015)	New AV (2015)
Fuel Economy	mi/gal	20.00	21.71	24.51	32.60	36.80
Fuel Damages GHG	cents/ gal	8.22	36.50	36.50	36.50	36.50
Fuel Damages Energy Security	cents/ gal	0.00	19.00	19.00	19.00	19.00
Accident Costs	cents/mi	4.11	2.70	2.70	2.70	2.70
Retail Price Gas no Tax	cents/ gal	128.82	178.00	178.00	178.00	178.00
Base Tax Rate Gasoline	cents/ gal	54.82*	48.86	48.86	48.86	48.86

Notes: All costs in $2016. P&S estimates for year 2000, new values for 2015.

- Fuel damages reflect an updated understanding of the costs of climate change damages provided by the Interagency Working Group on the social costs of GHGs and energy security costs used by the EPA/NHTSA, which primarily reflect marginal expected oil disruption costs.
- We place an asterisk on the gasoline tax rate to draw attention to the fact that had the average national gasoline tax rate increased with inflation it would now be higher than the current tax rate, 48.86 cents per gallon.
- P&S Base Gasoline Tax rate is the value used by P&S ($0.40/gal in $2000) adjusted to $2016 by GDP deflator.
- 2015 Base case tax of $0.4886 as reported in American Petroleum Institute State Motor Fuels Taxes Report, November 2016.

Results – Optimal Taxation

Using our base assumptions we find the efficient fuel tax for manual and automated vehicles is $2.04 vs $2.18 for on-road average and $2.20 vs $2.37 new 2015 MV and CAV. Thus, the efficient fuel tax is much higher than the current tax rate of $0.49 cents per gallon. Our results reflect the higher costs we assign to GHG damages and energy security costs and also the higher price of gasoline.

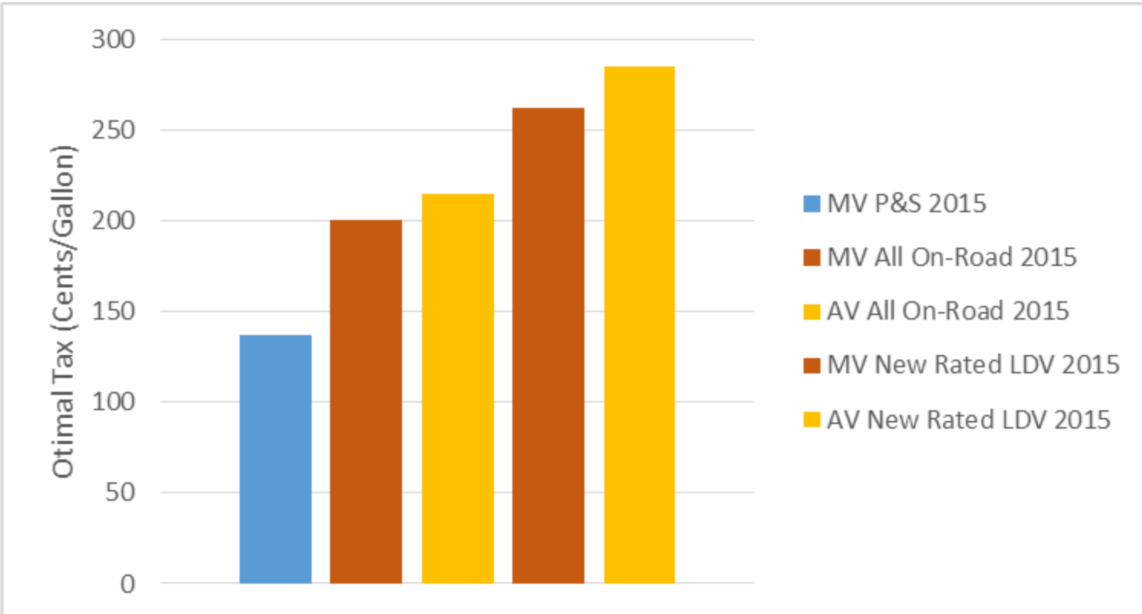

Figure 1: Optimal Fuel Tax for CAVs vs. MVs, Base Assumptions

The figure below shows that efficient fuel tax for an CAV, with its assumed 50% greater fuel efficiency, is larger than that for an MV. However, for any equivalent level of fuel economy, efficient fuel tax for an CAV is less than that for an MV due to the former's assumed lower time/congestion costs. The increases in the efficient fuel tax with time in the figure below are attributable to the assumed improvements in MPG, since we are controlling mile-based external costs with a tax on less fuel in each year.

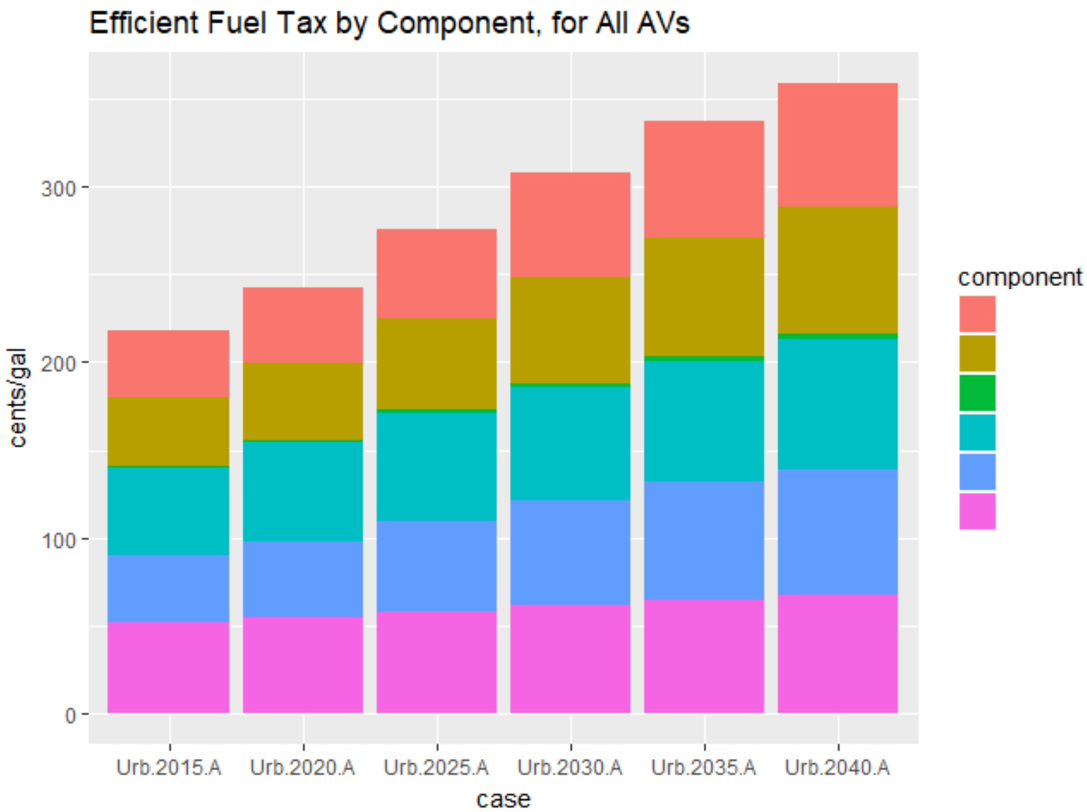

Figure 2: Variation in Efficient Fuel Tax for CAVs by Year

Not shown here graphically, but quite significant empirically, the efficient VMT tax rate for CAVs and MVs goes down over time due to the increase in vehicle fuel economy over time from increasing fuel efficiency standards. This is partly because our model has a balanced government budget requirement (no change in total revenues). Thus, when you raise a fixed amount of money from optimally combining labor tax and VMT tax, as fuel efficiency increases and more miles are driven the efficient tax per vehicle mile falls.

Methods – Social Acceptance and Use of Autonomous Vehicles

Given the complexity of travel choices, the use of insights from multiple disciplines is in order. Regulatory focus theory, from social psychology, notes that an individual's evaluation of, and choice among, alternatives is influenced by whether they are promotion or prevention focused. Individuals with a predominant promotion focus are concerned with advancement, growth and accomplishment – including an openness to change. In contrast, prevention-focused individuals are concerned with protection, safety and responsibility which align with key areas of concern related to autonomous vehicles. At present, we are aware of no work that uses regulatory focus theory to evaluate CAV acceptance and thus explore some aspects of regulatory focus theory in our work. Complicating our ability to predict the future use of CAVs is the fact that new vehicles may have varying levels of technology, ranging from Level 0 (traditional vehicles with no automation), Levels 2 and 3 with partial self-driving capacity, to Level 4 high automation (full automation in mode-specific circumstances) and Level 5 (full automation under all roadway conditions). These ranges of technologies present differing levels of attributes that a consumer may, or may not, desire in a vehicle. Thus we explicitly examine the role of differing levels of technology through our hypothesis that providing consumers with differing levels of potential vehicle technology will alter their acceptance of, perceptions of, and in-vehicle behaviors associated with, self-driving vehicles

Sampling and data collection
Our data is from a New England based (Maine, New Hampshire, Vermont, Rhode Island, Connecticut) mail survey, administered in a two-round modified Dillman method between January and March of 2017, with a response rate of 20%. Participants were randomly selected residents 18 years or older. Our respondents are less likely to have a child in the household, be older, have higher income and have attained higher levels of education than the New England population. We chose to set our work in the New England region, in order to capture perspectives from both rural and urban area citizens, as well as perceptions from drivers who experience varied seasonal driving conditions.

Survey Design
Early sections of the survey capture drivers' current travel behavior (mode, miles driven for various activities, and limiting conditions) as well as information on the respondents' current vehicle, including current driver assist technologies, participants evaluation of these technologies, and current habits in both a stopped and traveling vehicle.

Statistical methods
In order to address our hypotheses, we examine our data using descriptive and inferential statistics, as well as regression analysis. Analysis of variance and cross-tabs allows us to examine differences in response patterns associated with our embedded experiment on type of self-driving vehicle. Factor analysis enables us to identify relevant latent variables that capture attitudes toward autonomous vehicles, and implement them as covariates in a logistic model, which examines factors influencing participant's preferences for self-driving vehicle.

Results – Acceptance and Use of CAVs

Use and Trust of Vehicle Technology
Familiarity with, and acceptance of, autonomous vehicles may be influenced by consumers current use of vehicle technology, which is predicated by access to the technology. Interestingly, 21.7% of our sample indicate they never buy new cars. Of those respondents reporting that they will buy a new car, consumers planned, on average, to wait 4 years before their next purchase. Approximately one third (33%) of our respondents indicated it would be more than 5 years before they purchased a new vehicle. The population of car buyers is important to consider, as 22% of those who indicated they would prefer not-self-driving vehicles (in comparison to either 'partly' or 'completely' self-driving) also indicate they never buy new cars, only used. Thus, consumers in the secondary car market will be reliant on the primary market to determine much of the technology in future vehicles. Importantly, respondents with driver assist technologies in

their current vehicle evaluated these technologies far more positively than those who did not report having the technologies

Future Vehicle Technology
Our participants were mixed in their *Self-Reported Familiarity* with self-driving vehicles, with 47% reporting they were 'Not Familiar' with self-driving vehicles; in contrast, only 4% identified as 'familiar'. Even with this lack of familiarity, almost half of our participants indicated that they expected new cars to be completely self-driving on roads in their area by 2025. Respondents who were drivers, not passengers, indicated that they would engage in different behaviors depending on whether they were traveling in a partially, or completely self-driving vehicle, further confirming our second hypothesis. Survey participants were more likely to read a book, check emails/surf the internet/use social media, or use a mobile phone for texting in a completely self-driving vehicle than a partially self-driving. Engaging in use of phones for calling, listening to music, eating/drinking/smoking, interacting with other passengers and observing the scenery did not differ by level of self-driving vehicle. To further capture in-vehicle behavior changes with varying levels of vehicle autonomy, we collected baseline information on habits in a respondent's current vehicle, both moving and stopped. Perhaps not surprisingly, we find that driver activities in a stopped vehicle closely reflect their perceived future activities in an CAV. Respondents reported that they will engage in more non-driving behaviors in any type of autonomous vehicles; the only behaviors not experiencing increased frequency being eating/drinking, listening to music and interacting with other passengers. Interestingly, our respondents indicate they will interact with other passengers far *less* in autonomous vehicles than they do in moving or stopped current vehicles. One could conjecture that respondents envision sole-ridership in CAV vehicles, or will be so busy engaging in other activities that they will have little time for social interactions.

The introduction of CAVs to the driving fleet may also introduce *new in-car behaviors* that are currently unsafe to engage in with current vehicles. Respondents reported on the potential to engage in four new in-car behaviors: sleeping, watching movies/TV, using virtual reality (VR) and driving intoxicated/using drugs. Respondents are significantly more likely to engage in driving intoxicated, while using VR technology, watching movies/TV and sleeping in a completely self-driving vehicle in comparison to a partially self-driving vehicle.

Factors impacting intent to use
When given the opportunity to express preferences about the level of technology preferred in a personal vehicle, 57% of respondents preferred non self-driving vehicles. Thirty-one percent preferred partially self-driving vehicles, and only 12% preferred completely self-driving.

Current Travel Behavior and Technology Use
We captured information on current travel behavior and technology use to determine if these impact CAV acceptance. Miles traveled yearly, as well as daily travel time, were found to be highly correlated. Given that CAVs may be associated with changes in travel time opportunity cost, we include only *Drivetime* and not *Miles* in our regression. Interestingly, none of the variables intended to capture current travel decisions are significant in explaining CAV acceptance.

Performance and Effort
Consistent with the CTAM, we attempted to capture effort and performance expectations for CAV adoption. We find that lower perceived effort needed to become skilled at using the vehicle, and positive expectations of performance significantly, positively impacted stated interest in vehicle technology (β=0.64, p<.0001). Further, fear of losing control of vehicle performance and loss of driving skills, decreases acceptance of CAVs (β=-0.35, p=.042). Interestingly, a focus on technology as challenging and unnecessary has a significant negative impact on CAV acceptance (β=-0.28, p=.050), but higher trust in science and technology had no impact (β=-0.004, p=.980).

Perceived Safety and Familiarity
Perception that CAV technology is safe, perhaps more so than human drivers (*Perceived safety*) positively influences CAV acceptance. The perceived importance of *Potential Benefits* also has a marginal positive impact on CAV acceptance while neither the importance of concerns (*Potential Concerns*) nor the *Self-Reported Familiarity* exerted significant influence.

Sociodemographics
We do not find a significant effect of gender, but we do find that households with children are less likely to indicate use, and that neither income nor age are significant. We also find that car-centric recreation is not an impacting factor. To enhance our understanding of personal characteristics that may affect the decision to accept (or not) autonomous vehicles, we also include the promotion and prevention scales from regulatory focus theory. Consistent with our expectations, we find that prevention oriented individuals are less likely to indicate acceptance of autonomous vehicles.

Conclusions
Rethinking our current transportation infrastructure to incorporate autonomous vehicles is a daunting task. The way forward remains unclear, in no small part due to the uncertainty surrounding consumer adoption of CAVs. Using consensus estimates of the external costs of driving including damages from GHG and criteria emissions, the costs from oil dependency, accident and congestion costs and the inefficiencies from taxing driving, we determine the efficient tax levels for CAV road travel. We find that the fully efficient level of fuel taxes would be much higher, in the range of more than $2.00 per gallon or about 4 times the current level. This is true for both CAVS and MVs. These levels of taxation may not be socially acceptable in the US in the near future. Fuel taxes in this range are found in 29 of 33 OECD countries however, and would provide significant revenues to pay to transportation infrastructure, reduce the national debt or lower taxes on work and investments. Under the expectation of significant fuel efficiency gains for CAVs compared to MVs, we find that the efficient fuel tax level for CAVs is greater than that of MVs, despite their reduced fuel use and ability to reduce external congestion and travel time costs. This seemingly perverse conclusion that CAVs that should have a higher fuel tax is the result of controlling both fuel-based and mileage-based external costs with a single fuel-based tax. However, the fuel tax on CAVs is lower when they have the same fuel economy as MVs. Furthermore, we show that to the extent that CAVs have lower accident rates and external costs than MVs, their fuel tax rate should be significantly lower as well.

In order for CAVs to be used, they must be voluntarily purchased. Our findings suggest the importance of identifying an individual's existing technology attitudes, and personal characteristics, in understanding their CAV adoption decision. Our work suggests CAVs will be evaluated differently by different members of the public. Additionally, we find that it is important how CAVs are introduced to the public. Participants who fear losing control and see technology as a challenge are less willing to adopt the technology; the concerns that drivers see related to CAVs are not necessarily about the product itself, but rather their personal capacity to adapt to these changes. Benefits are also important in the adoption decision and we find that participants more highly evaluate technology they are currently using in their vehicles, and indicate higher levels of comfort with partially self-driving vehicles. This suggests that transportation decision makers may wish to consider a 'tiered' release of self-driving vehicles to allow for consumers to experience the performance of the vehicles, realize a lower effort threshold in becoming capable of operating these vehicles, and allowing for stronger feelings of control, all directly addressing concerns highlighted by this work.

Finally, our respondents state that they will change their use of in-vehicle time given different levels of automation. At higher levels of automation, we find a stated willingness of 'drivers' to engage in four new in-car behaviors: sleeping, watching movies/TV, using virtual reality and driving intoxicated/using drugs. This change in behavior is likely to lead to change in the use of private automobiles since vehicle travel time is one of largest costs associated with travel. This may well lead to changes in urban and suburban land use patterns as drivers re-evaluate the costs and benefits of travel.

While our work provides additional insight into factors which affect autonomous vehicle acceptance and potential use, we recognize that our work has limitations. As with all stated data, individuals may recognize that there are no consequences of responses, and therefore may not reveal preferences truthfully. Further, while we gather information on our respondents current travel behavior, we do not know all of the structural constraints they may face in making travel choices. Finally, while our data provides interesting insights into preferences for CAVs, our New England only sample may limit the generalizability of our results.

Publications

Rubin, Jonathan. 2016. "Connected Autonomous Vehicles: Travel Behavior and Energy Use." In Road Vehicle Automation 3, edited by Gereon Meyer and Sven Beiker, 151–62. Cham: Springer International Publishing. http://dx.doi.org/10.1007/978-3-319-40503-2_12.

Noblet, Caroline L., Jonathan Rubin, Allyson Eslin, Ryan Jennings, "What's 'Driving' Adoption of Automated Vehicles: Attitudes and Perceptions of Benefits and Risks, TRB 2018 Annual Meeting Compendium, forthcoming.

Leiby, Paul and Jonathan Rubin, "Efficient Fuel and VMT Taxation for Automated Vehicles, *Transportation Research Record: Journal of the Transportation Research Board*, revised and resubmitted.

Presentations

Leiby, Paul and Jonathan Rubin, "Efficient Fuel and VMT Taxation for Automated Vehicles," accepted for presentation at the TRB 2018 Annual Meeting.

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Noblet, Caroline L., Jonathan Rubin, Allyson Eslin, Ryan Jennings, "What's 'Driving' Adoption of Automated Vehicles: Attitudes and Perceptions of Benefits and Risks," accepted for presentation at the TRB 2018 Annual meeting.

Leiby, Paul and Jonathan Rubin, "Incentives to Promote Sustainable Energy Outcomes with Connected Autonomous Vehicles: Taxation Strategies and Energy/Demand Responses," Automated Vehicles Symposium 2017, San Francisco, July 11, 2017.

Noblet, C.L., Rubin, J. and R. Jennings. Perceptions of Self-Driving Vehicles and Impact on Demand. Maine Economics Conference. April 29, 2017. Colby College Waterville, Maine.

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Rubin, Jonathan and Paul Leiby, "Economic Incentives for Vehicle Automation & Implications for its Likely Features," Second International Conference of the Sustainable Consumption Research and Action Initiative (SCORIA), Transitions Beyond a Consumer Society, University of Maine, Orono, ME, USA , June 15–17, 2016, http://scorai.org/scorai-2016/.

Rubin, Jonathan, "Connected Automated Vehicles: AVs: Relationship to Travel Behavior & Energy Use," Automated Vehicles Symposium 2015, sponsored by the Association for Unmanned Vehicle Systems International and Transportation Research Board of the National Academics, Ann Arbor, Michigan July 21-23.