Preliminary Investigation   (PI-0014)

Caltrans Division of Research, Innovation and System Information

DRISI

Environmental Impacts of
Connected and Automated Vehicles

Requested by
Chris Ganson, Governor's Office of Planning and Research

February 2, 2018

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Executive Summary

Background

Connected vehicle (CV) and automated (or autonomous) vehicle (AV) technologies are being developed, tested and deployed by a variety of private companies and public agencies. CVs and AVs are likely to affect safety, access, transportation equity, emissions, vehicle miles traveled (VMT), and the efficiency and reliability of the transportation system. While early assessments of the effects of these technologies requires making assumptions and necessarily involves some speculation, ascertaining potential impacts is critical to policy development as market penetration rates are expected to increase.

Caltrans and its partners are seeking information about the impact of connected and automated vehicles (CAVs) on greenhouse gas (GHG) emissions and VMT, and the range of associated benefits or challenges. Of particular interest is the impact of CAVs on travel behavior and how these changes in behavior may affect traffic and function of the roadway, transit use, mode shift, human health, the environment, transportation equity, land use and livability.

To gather information for this Preliminary Investigation, CTC & Associates reviewed recently published and in-process research and related resources that assess the future use of CAVs and attempt to predict associated impacts on GHG and VMT.

Summary of Findings

This report provides a sampling of recent research and related publications addressing the potential impacts of CAVs, with a greater focus on domestic rather than international efforts. The tables beginning on page 4 summarize the publications and research in progress highlighted in this Preliminary Investigation in these topic areas:

- Environmental and Greenhouse Gas Impacts.

- Impact on Vehicle Miles Traveled.

- Equity, Public Health and Social Impacts.

- Roadway Impacts.

- Other Impacts.

    - Land Use and Livability.

    - Last-Mile Service.

    - Travel Behavior.

- Planning, Modeling and Evaluation.

The tables are presented in the order of the topic areas listed above. Each table provides the publication or project title and the year of publication (research in progress is noted without a year); the type of vehicle addressed in the publication or research (AV, CV or CAV); the type of research or result (such as projections and estimates, recommendations and benefits); and a brief description of project findings. More information about each publication, including a link to the full text or citation, can be found in the **Detailed Findings** section of this report, which mirrors the order in which the publication appears in the summary tables.

Gaps in Findings

Many researchers are examining the environmental and other impacts of the widespread adoption of CAV technology, and the literature describing these efforts shows considerable range in GHG emissions and VMT outcomes. The research shows that estimates depend heavily on how AVs are deployed.

We identified several research projects in progress that are expected to conclude in 2017 and 2018. A few projects in progress appear to have concluded (in 2016 or 2017), but a final report is not publicly available. Findings from these projects may provide more substantial guidance on the environmental impacts of CAVs.

Next Steps

Moving forward, Caltrans could consider:

- Consulting with departments of transportation (DOTs) and transportation researchers about efforts to prepare for the arrival of widespread CAV technology. Possible contacts include:
    - Texas DOT, to discuss a range of research efforts associated with the impacts of CAVs.
    - Center for Connected and Automated Transportation, to discuss the research in progress examining AVs' impact on energy demand and GHG emissions.
    - Technologies for Safe and Efficient Transportation (national University Transportation Center for safety), to discuss research underway that considers options for the Pennsylvania Turnpike to begin transitioning to accommodating CAVs.
    - Institute of Transportation Studies at the University of California, Davis, to learn more about the 3 Revolutions Policy Initiative (see https://3rev.ucdavis.edu/).
    - Institute of Transportation Studies at the University of California, Berkeley, to engage with researchers, including Susan Shaheen and Joan Walker.

- Tracking the research in progress, including making inquiries about final reports associated with projects expected to conclude in 2016 and 2017.

- Examining the publications offering specific projections and estimates to compare and contrast researchers' assumptions and conclusions.

- Reviewing in detail the publications addressing planning and modeling to identify areas for further investigation.

Environmental and Greenhouse Gas Impacts

Publication or Project (Year)	Vehicle Type	Type of Research/Result	Description
AV's Impacts on Energy Demand and GHG Emissions (Research in Progress)	AV	Projections and estimates	Expected to develop improved projections of future travel demand and patterns, and an estimate of energy and carbon intensity of vehicle travel. Completion date: February 2018.
Environmental Impacts of Automated Vehicles (Research in Progress)	AV	Meta-analysis of research	Expected to synthesize best research available and highlight research gaps. Completion date: October 2016 (no report available).
Development of Integrated Vehicle and Fuel Scenarios for Low Carbon US Transportation Futures (Research in Progress)	AV	Projections and estimates; modeling	Expected to include model development, assessment of capital and operating costs of vehicle technologies and fuel infrastructure; will also provide estimates of GHG reductions, costs and policy pathways. Completion date: September 2017 (no report available).
Keeping Vehicle Use and Greenhouse Gas Emissions in Check in a Driverless Vehicle World (2017)	CAV	Recommendations	Provides policy recommendations to support VMT and GHG containment goals.
Study of the Potential Energy Consumption Impacts of Connected and Automated Vehicles (2017)	CAV	Potential for impact	Identifies CAV-enabled factors with greatest impact on increasing energy consumption (reduced travel cost, higher highway speeds, longer commute distances and inclusion of previously underserved user groups).
Analysis of the Potential of Autonomous Vehicles in Reducing the Emissions of Greenhouse Gases in Road Transport (2017)	AV	Potential for impact	Analyzes the potential for AV to reduce GHG emissions.
Assessing Autonomous Vehicle Impact on Urban Traffic Emissions and Intersection Performance (2016)	AV	Projections and estimates; modeling	Examines environmental performance of mixed traffic streams (driverless and conventional) using instantaneous vehicle emission modeling.
Fuel Economy Testing of Autonomous Vehicles (2016)	AV	Projections and estimates	Examines fuel economy testing of AV; can degrade fuel economy by up to 3% (no consideration of efficiency).
Help or Hindrance? The Travel, Energy and Carbon Impacts of Highly Automated Vehicles (2016)	AV	Projections and estimates	Concludes that AVs might reduce GHG emissions and energy use by nearly half—or nearly double them—depending on which effects come to dominate. Notes that many potential energy-reduction benefits may be realized through partial automation, while major energy/emission downside risks appear more likely at full automation.

Environmental and Greenhouse Gas Impacts

Publication or Project (Year)	Vehicle Type	Type of Research/Result	Description
Estimate of Fuel Consumption and GHG Emission Impact from an Automated Mobility District (2015)	AV	Projections and estimates	Provides framework to quantify the fuel consumption and GHG emission impacts of a transit system composed of AVs (an automated mobility district, or AMD). AMD has the potential to reduce total system fuel consumption and GHG emissions; the amount is largely dependent on operating and ridership assumptions.
An Analysis of Possible Energy Impacts of Automated Vehicles (2014)	AV	Projections and estimates	Concludes that widespread AV deployment can lead to dramatic fuel savings but has the potential for unintended consequences.
The Future of Fully Automated Vehicles: Opportunities for Vehicle- and Ride-Sharing, with Cost and Emissions Savings (2014)	AV	Projections and estimates	Estimates shared AV use leads to 16% less energy use and 48% lower volatile organic compound emissions per person-trip formerly served by a household vehicle.
Environmental and Energy Impacts of Automated Electric Highway Systems (2013)	AV	Projections and estimates; modeling	Uses Motor Vehicle Emission Simulator (MOVES) program to estimate the impacts on emissions and energy use associated with hypothetical implementation of automated electric highway systems on Interstate 70 in Missouri during 2011-2040: • Decreases fossil fuel energy use by more than 25%. • Emissions decrease by up to 27% depending on the pollutant. • 10% reduction in VMT has effect of 5% or less on the criteria of interest.

Impact on Vehicle Miles Traveled

Publication or Project (Year)	Vehicle Type	Type of Research/Result	Description
Estimating Safety Benefits and Costs and Changes in Vehicle Miles Traveled from Vehicle Automation (Research in Progress)	CAV	Projections and estimates	Expected to examine costs and bounds on increases in VMT associated with CAVs. Completion date: January 2017 (no report available).
An Assessment of Autonomous Vehicles: Traffic Impacts and Infrastructure Needs—Final Report (2017)	AV	Projection and estimates	Examines public perception toward technologies and describes impacts of AVs in Texas, concluding that AVs will lead to increased VMT.

Impact on Vehicle Miles Traveled

Publication or Project (Year)	Vehicle Type	Type of Research/Result	Description
Analysis of the Impacts of CAV Technologies on Travel Demand (2017)	CAV	Projections and estimates; modeling	Uses POLARIS to determine a potential range of VMT impacts from various technologies.
Autonomous Vehicles: Hype and Potential (2016)	AV	Projections and estimates	Projects that until standard private vehicles and trucks are eliminated, AVs will lead to increased VMT—one-third more for personal AV and up to twice as many for unshared AV taxis.
Shifts in Long-Distance Travel Mode Due to Automated Vehicles: Statewide Mode-Shift Simulation Experiment and Travel Survey Analysis (2016)	AV	Projections and estimates; modeling	Highlights shifts in mode choices and the impact of travel distance.
Potential Impact of Self-Driving Vehicles on Household Vehicle Demand and Usage (2015)	AV	Projections and estimates	Provides upper bound estimate for sharing of AVs (reduce average vehicle ownership rates by 43%; results in 75% increase in individual vehicle usage; no estimate of additional miles generated).
Bounding the Potential Increases in Vehicles Miles Traveled for the Non-Driving and Elderly Populations and People with Travel-Restrictive Medical Conditions in an Automated Vehicle Environment (2015)	AV	Projections and estimates	Estimates an upper bound of a 12% increase in overall VMT (an upper bound, not a forecast of specific VMT scenarios).

Equity, Public Health and Social Impacts

Publication or Project (Year)	Vehicle Type	Type of Research/Result	Description
Public Health, Ethics and Autonomous Vehicles (2017)	AV	Recommendations	Recommends four areas to explore for ethical impact (forced-choice algorithms under development by manufacturers; expanding the public's awareness; facilitating the inclusion of the historically disenfranchised in the discussion; and ensuring consistent regulations across states).
Can We Advance Social Equity with Shared, Autonomous and Electric Vehicles? (2017)	AV	Benefits	Discusses how AVs can benefit historically disadvantaged communities.

Equity, Public Health and Social Impacts

Publication or Project (Year)	Vehicle Type	Type of Research/Result	Description
Equity, Safety and Privacy in the Autonomous Vehicle Era (2016)	CAV	Risks and benefits	Examines privacy risks associated with CAVs.
Environmental Justice Considerations for Connected and Automated Vehicles (2016)	CAV	Risks and benefits	Cautions decision-makers to consider equity concerns and ensure that environmental justice populations do not experience disproportionately high and adverse human health or environmental effects.

Roadway Impacts

Publication or Project (Year)	Vehicle Type	Type of Research/Result	Description
Strategic and Tactical Guidance for the Connected and Autonomous Vehicle Future (Research in Progress)	CAV	Projections and estimates	Expected to synthesize the existing state of practice; estimate the impact of headway distribution and traffic signal coordination; and provide a strategic roadmap for Indiana DOT in preparing for and responding to potential issues. Completion date: June 2018.
Transitioning Roadways to Accommodate Connected and Automated Vehicles: A Pennsylvania Case Study (Research in Progress)	CAV	Analysis of options	Expected to assess options for the Pennsylvania Turnpike to begin transitioning to accommodating CAVs.
Blueprint for Autonomous Urbanism (2017)	CAV	Projections and estimates; recommendations	Examines the potential of city streets, intersections and networks and the impact of automation in "serv[ing] the goals of safety, equity, public health and sustainability."
Developing "Highway Capacity Manual" Capacity Adjustments for Agency Connected and Autonomous Vehicle Operational Planning Readiness under Varying Levels of Volume and Market Penetration (2017)	CAV	Projections and estimates	Develops "the highway capacity adjustments for CAVs at different levels of volume and market penetration in order to adapt the use of HCM [Highway Capacity Manual] in analyzing CAV applications."
Assessing the Potential Impacts of Connected Vehicles: Mobility, Environmental and Safety Perspectives (2016)	CV	Projections and estimates; modeling	Shows quantitatively how the market penetration of CVs affects performance of the traffic network.

Roadway Impacts

Publication or Project (Year)	Vehicle Type	Type of Research/Result	Description
Effects of Next-Generation Vehicles on Travel Demand and Highway Capacity (2014)	AV	Projections and estimates	Examines effects of AVs on traffic generation, highway capacity and congestion over time.

Land Use and Livability

Publication or Project (Year)	Vehicle Type	Type of Research/Result	Description
Impact of Transformational Technologies on Land Uses (Anticipated Research)	CAV	Projections and estimates	Expected to document "potential and likely changes in site selection and demand for retail, office, distribution, production, housing and parking land due to development of transformational technologies."
Land Use and Transportation Policies (2017)	CAV	Recommendations	Presents policy recommendations for land use and transportation planning; also addresses opportunities for future research.
Autonomous Vehicles and Commercial Real Estate (2016)	AV	Projections and estimates	Projects that the total vehicle count may decrease with AV use, allow for the narrowing of roads and conversion of extra space, and decrease the amount of impervious surface. Greatest impacts expected in lower-density areas and suburbs; central business districts may see little impact.

Last-Mile Service

Publication or Project (Year)	Vehicle Type	Type of Research/Result	Description
Shared Autonomous Vehicles as a Sustainable Solution to the Last Mile Problem: A Case Study of Ann Arbor-Detroit Area (2017)	AV	Projections and estimates	Examines impact of shared AV taxi system providing last-mile transit services; concludes that energy savings were as high as 37% when compared to the use of personal vehicles.

Travel Behavior

Publication or Project (Year)	Vehicle Type	Type of Research/Result	Description
Developing a Platform to Analyze Behavioral Impacts of Connected Automated Vehicles at the National Level (2017)	CAV	Projections and estimates; modeling	Uses POLARIS to estimate the potential regional impacts of CAV technologies, with an interest in considering national travel behavior.
Towards an Understanding of the Travel Behavior Impact of Autonomous Vehicles (2017)	AV	Projections and estimates; modeling	Provides empirical evidence about AV use that indicates most respondents would rather own self-driving vehicles (59%) than just use one (41%); using one would have no change on where people would choose to live (80%); and no change to VMT (66%).

Planning

Publication or Project (Year)	Vehicle Type	Type of Research/Result	Description
Impacts of Connected Vehicles and Automated Vehicles on State and Local Transportation Agencies—Task-Order Support (Ongoing Task-Based Research)	CAV	Wide range of task-related research	See page 25 of this Preliminary Investigation for information about this wide-ranging NCHRP project that examines critical issues associated with CAVs.
NCHRP 20-24(98): Connected/Automated Vehicle Research Roadmap for AASHTO (2015)	CAV	Proposed research	Provides the research roadmap for addressing the CAV issues described in the citation above; includes descriptions of 23 proposed research projects.
NCHRP Report 845: Advancing Automated and Connected Vehicles: Policy and Planning Strategies for State and Local Transportation Agencies (2017)	CAV	Policy and planning strategies	Presents 18 strategies in the following categories: mitigate safety risks; encourage shared AV use; address liability issues; and enhance safety, congestion and air quality benefits by influencing market demand.
Transportation Planning Implications of Automated/Connected Vehicles on Texas Highways (2017)	CAV	Policy and planning strategies	Assesses how CAV technologies can be included in transportation planning to assist the decision-making process.
3 Revolutions Policy Briefs (2017)	CAV	Policy and planning strategies	Presents policy challenges, recommendations and research needs in a series of policy briefs that examine CAV-related issues associated with active travel, climate, equity, governance and transit.

Modeling

Publication or Project (Year)	Vehicle Type	Type of Research/Result	Description
Travel Modeling in an Era of Connected and Automated Transportation Systems: An Investigation in the Dallas-Fort Worth Area (2017)	CAV	Policy and planning strategies; projections and estimates	Uses travel modeling to contrast AV and CV technologies; examine adoption predictions; and describe 112 proposed potential planning scenarios identifying CAV impacts.
Modelling the Impact of Automated Driving—Private Autonomous Vehicle Scenarios for Germany and the U.S. (2016)	AV	Projections and estimates	Forecasts travel by different traveler groups and by car availability (no car, conventional car, AV); results show "a ~5% increase in VMT for both Germany and the USA, resulting from somewhat longer trips combined with slight modal shifts from other modes towards the car."
Using an Activity-Based Model to Explore Possible Impacts of Automated Vehicles (2015)	AV	Projections and estimates	Shows that improvements in roadway capacity and quality of the driving trip may lead to large increases in VMT; a shift to per-mile usage charges may counteract that trend. Researchers recommend travel model improvements to address shared-ride and taxi modes.
Assessing the Long-Term Effects of Autonomous Vehicles on Mode Choice Behavior: A Speculative System Dynamics Approach (2015)	AV	Projections and estimates; policy and planning strategies	Finds that AV use may "lead to undesired results like more congestion and more emissions"; includes a discussion of potential policy interventions to encourage positive outcomes.
The Travel and Environmental Implications of Shared Autonomous Vehicles, Using Agent-Based Model Scenarios (2014)	AV	Projections and estimates	Examines shared AVs (SAVs), finding that each SAV can replace around 11 conventional vehicles but adds up to 10% more travel distance than comparable non-SAV trips.

Evaluation

Publication or Project (Year)	Vehicle Type	Type of Research/Result	Description
Performance Measurement Evaluation Framework and Co-Benefit/Tradeoff Analysis for Connected and Automated Vehicles (CAV) Applications: A Survey (2017)	CAV	Projections and estimates; benefits	Classifies CAV applications and identifies factors influencing system performance and suggests approaches for obtaining benefits across different measures of effectiveness.
Benefits Estimation Framework for Automated Vehicle Operations (2015)	AV	Projections and estimates; benefits	Estimates benefits and challenges with regard to safety; vehicle mobility; energy and the environment; accessibility; transportation system usage; land use; and economic analysis.

Detailed Findings

The citations included in this Preliminary Investigation represent a sampling of recent research and related publications addressing the potential impacts of connected and automated vehicles (CAVs) on greenhouse gas (GHG) emissions and vehicle miles traveled (VMT) and the range of associated benefits or challenges. Given the wealth of information associated with this general topic, the publications cited in this report reflect an emphasis on recent research and a greater focus on domestic rather than international efforts.

The publications and related resources that follow are organized in the following categories:

- Environmental and Greenhouse Gas Impacts.

- Impact on Vehicle Miles Traveled.

- Equity, Public Health and Social Impacts.

- Roadway Impacts.

- Other Impacts.
    - Land Use and Livability.
    - Last-Mile Service.
    - Travel Behavior.

- Planning, Modeling and Evaluation.

Environmental and Greenhouse Gas Impacts

Research in Progress: AVs' Impacts on Energy Demand and GHG Emissions, Center for Connected and Automated Transportation, project start date: March 2017, expected completion date: February 2018.
Project description at http://ccat.umtri.umich.edu/wp-content/uploads/2017/08/AV-Impacts-on-Energy-Demand-and-GHG-Emissions.pdf
From the abstract: The objective of the proposed work is to examine the potential effects of automation on energy demand and GHG emissions from vehicles. To achieve this, improved projections of future travel demand and patterns in response to AVs [automated, or autonomous, vehicles] will be obtained using a behavioral experiment (survey and focus groups), and the energy and carbon intensity of vehicle travel will be estimated.

Research in Progress: Environmental Impacts of Automated Vehicles, National Center for Sustainable Transportation, project start date: November 2015, expected completion date: October 2016. (The center's web site does not provide a link to the completed white paper.)
Project description at https://ncst.ucdavis.edu/wp-content/uploads/2015/10/02-02-2016-Rodier-Project-Info-Form-.pdf
From the project description: The proposed National Center's white paper will focus on the environmental effects of automated vehicles. The white paper will provide a framework to understand the dimensions of the environmental effects of automated vehicles. It will synthesize the best research available on this topic, and will highlight important research gaps. It will make clear the link between research findings and policy implications. The most seminal and relevant reports on the topic will be reviewed. To the extent possible, the focus will be on peer-reviewed

and/or publicly accessible analyses. Given that this is such a new research topic, the literature may be supplemented with expert interviews.

Research in Progress: Development of Integrated Vehicle and Fuel Scenarios for Low Carbon US Transportation Futures, National Center for Sustainable Transportation, project start date: October 2016, expected completion date: September 2017.
Project description at https://ncst.ucdavis.edu/wp-content/uploads/2016/10/08-24-2016-USDOT_Yang_Y3_projectinfo.pdf
From the project description: The objective of this project is to better understand the greenhouse gas emissions (GHG) reduction potential in the U.S. transportation sector, with a focus on advanced vehicle technologies including zero emission vehicles and low-carbon, alternative fuels. The researchers will analyze a range of potential transition scenarios toward low-carbon transportation futures in the United States exploring how policies and technology assumptions impact vehicle, fuel infrastructure and resource requirements and costs. The analysis will be carried out through development of a national level U.S. energy economic optimization model (US-TIMES), employing the widely-used MARKAL/TIMES framework). They will address critical "gaps" in existing transportation energy models by (1) providing detailed representation of all major transportation subsectors at a disaggregated level (light-duty, medium and heavy-duty, rail, marine, aviation and off-road); (2) focusing model development on investments in both vehicles and fuel infrastructure; (3) assessing capital and operating costs of vehicle technologies and fuel infrastructure; and (4) using an integrated model to understand important linkages/synergies between the transport and other energy sectors. The proposed work will enable the development of robust, full U.S. transport sector scenarios for 2030 and 2050, and estimates of GHG reductions, costs, and policy pathways to achieving them.

Keeping Vehicle Use and Greenhouse Gas Emissions in Check in a Driverless Vehicle World, Giovanni Circella, Chris Ganson and Caroline Rodier, Policy Brief, 3 Revolutions Policy Initiative, Institute of Transportation Studies, University of California, Davis, April 2017.
https://3rev.ucdavis.edu/wp-content/uploads/2017/04/3R.VMT-GHG.final_-1.pdf
This policy brief includes the following policy recommendations "to support VMT and GHG containment goals":

1. Deploy driverless vehicles as shared use vehicles, rather than privately owned.

2. Ensure widespread carpooling.

3. Deploy driverless vehicles with zero tailpipe emissions.

4. Take advantage of opportunities to introduce pricing.

5. Increase line haul transit use rather than replacing it.

6. Ensure driverless vehicles are not larger or more energy consumptive.

7. Program vehicle behavior to improve livability, safety and comfort on surface streets.

Study of the Potential Energy Consumption Impacts of Connected and Automated Vehicles, U.S. Department of Energy, March 2017.
https://www.eia.gov/analysis/studies/transportation/automated/pdf/automated_vehicles.pdf
From the preface:

This report considers the impacts of autonomous vehicles through 2050. Because of the early state of the industry and the high level of uncertainty, the 2026–2031 period (10–15 years in the future) was the primary focus for potential impacts.

This report presents results from a comprehensive literature review as well as input from limited expert interviews about the technical, societal, and economic impacts of the deployment of autonomous vehicles. The study focused on determining the potential impacts of these vehicles on energy consumption over time via estimates of potential market penetration.

Energy impacts are summarized on page iv of the report (page 9 of the PDF):

Vehicle energy consumption strongly depends on three interdependent variables: vehicle miles traveled, vehicle efficiency, and the travel cost (basis for consumer adoption). Automated vehicles provide functionality and services that could both increase or decrease energy consumption. CAV-enabled factors that could have the greatest impact on decreasing energy consumption include: 1) vehicle lightweighting and rightsizing, 2) powertrain electrification, 3) platooning, and 4) eco-driving. Conversely, CAV-enabled factors that could have the greatest impact on increasing energy consumption are: 1) reduced travel cost, 2) higher highway speeds, 3) longer commute distances, and 4) inclusion of previously unserved/underserved user groups (e.g., elderly, disabled, and young people).

"Analysis of the Potential of Autonomous Vehicles in Reducing the Emissions of Greenhouse Gases in Road Transport," Hubert Igliński and Maciej Babiak, *Procedia Engineering*, Vol. 192, pages 353-358, 2017.
Citation at https://doi.org/10.1016/j.proeng.2017.06.061 (click on "Download full text in PDF" to obtain the full text of this open-access article)
From the abstract: The aim of [the] authors of this paper is to analyze the potential for AV to reduce GHG emissions from road transport. The analysis includes not only technical and technological issues, but also organizational [issues] and in the management of transport demand.

"Assessing Autonomous Vehicle Impact on Urban Traffic Emissions and Intersection Performance," Konstantinos Zavitsas, Simon Hu, Roxanne Gooden, Panagiotis Angeloudis and John Polak, *TRB 95th Annual Meeting Compendium of Papers*, Paper #16-0197, 2016.
Citation at http://trid.trb.org/view/1392268
From the abstract: This paper exploits the potential contribution of autonomous vehicles towards sustainable urban transport through their interaction with conventional traffic. Anticipating the gradual increase in autonomous vehicles use, the research examines how the adoption of a non-aggressive, environmentally friendly driving style from a varying percentage of the traffic may influence the driving style of the rest of the traffic, taking into account, system capacity, vehicle performance and user comfort indicators. Although autonomous vehicles can be powered either by conventional internal combustion or electric engines, the contribution to urban transport sustainability examined in this research concerns the assessment of the potential environmental benefits that might arise from mixed traffic streams (driverless and conventional). The research uses microscopic traffic simulation to assess the performance of mixed traffic streams. The environmental performance of the integrated traffic flow is assessed using instantaneous vehicle emission modelling for different levels of autonomous vehicle market penetration.

"Fuel Economy Testing of Autonomous Vehicles," Avi Chaim Mersky and Constantine Samaras, *Transportation Research Part C: Emerging Technologies*, Vol. 65, pages 31-48, April 2016.
Citation at http://trid.trb.org/view/1399938
From the abstract: By design, the current standardized fuel economy testing system neglects differences in how individuals drive their vehicles on the road. As autonomous vehicle (AV) technology is introduced, more aspects of driving are shifted into functions of decisions made by the vehicle, rather than the human driver. This paper develops a method to incorporate the impacts of AV technology within the bounds of current fuel economy test, and simulates a range of automated following drive cycles to estimate changes in fuel economy. The results show that AV following algorithms designed without considering efficiency can degrade fuel economy by up to 3%, while efficiency-focused control strategies may equal or slightly exceed the existing Environmental Protection Agency (EPA) fuel economy test results, by up to 10%. This suggests the need for a new near-term approach in fuel economy testing to account for connected and autonomous vehicles. As AV technology improves and adoption increases in the future, a further reimagining of drive cycles and testing is required.

"Help or Hindrance? The Travel, Energy and Carbon Impacts of Highly Automated Vehicles," Zia Wadud, Don MacKenzie and Paul Leiby, *Transportation Research Part A: Policy and Practice*, Vol. 86, pages 1-18, April 2016.
Citation at http://trid.trb.org/view/1402049
From the abstract: In this paper, the authors identify specific mechanisms through which automation may affect travel and energy demand and resulting GHG emissions and bring them together using a coherent energy decomposition framework. The authors review the literature for estimates of the energy impacts of each mechanism and, where the literature is lacking, develop their own estimates using engineering and economic analysis. The authors consider how widely applicable each mechanism is, and quantify the potential impact of each mechanism on a common basis: the percentage change it is expected to cause in total GHG emissions from light-duty or heavy-duty vehicles in the U.S. The authors' primary focus is travel related energy consumption and emissions, since potential lifecycle impacts are generally smaller in magnitude. The authors explore the net effects of automation on emissions through several illustrative scenarios, finding that automation might plausibly reduce road transport GHG emissions and energy use by nearly half—or nearly double them—depending on which effects come to dominate. The authors also find that many potential energy-reduction benefits may be realized through partial automation, while the major energy/emission downside risks appear more likely at full automation. The authors close by presenting some implications for policymakers and identifying priority areas for further research.

"Estimate of Fuel Consumption and GHG Emission Impact from an Automated Mobility District," Yuche Chen, Stanley Young, Xuewei Qi and Jeffrey Gonder, *2015 International Conference on Connected Vehicles and Expo (ICCVE) Proceedings*, pages 271-278, 2015.
Citation at http://trid.trb.org/view/1426017
From the abstract: This study estimates the range of fuel and emissions impacts of an automated-vehicle (AV)-based transit system that services campus-based developments, termed an automated mobility district (AMD). The study develops a framework to quantify the fuel consumption and greenhouse gas (GHG) emission impacts of a transit system comprised of AVs, taking into consideration average vehicle fleet composition, fuel consumption/GHG emission of vehicles within specific speed bins, and the average occupancy of passenger vehicles and transit vehicles. The framework is exercised using a previous mobility analysis of a personal rapid transit (PRT) system, a system that shares many attributes with envisioned AV-based transit systems. Total fuel consumption and GHG emissions with and without an AMD

are estimated, providing a range of potential system impacts on sustainability. The results of a previous case study based on a proposed implementation of PRT on the Kansas State University (KSU) campus in Manhattan, Kansas, serve as the basis for estimating personal miles traveled supplanted by an AMD at varying levels of service. The results show that an AMD has the potential to reduce total system fuel consumption and GHG emissions, but the amount is largely dependent on operating and ridership assumptions. The study points to the need to better understand ride-sharing scenarios and calls for future research on sustainability benefits of an AMD system at both vehicle and system levels.

"An Analysis of Possible Energy Impacts of Automated Vehicles," Austin Brown and Jeffrey Gonder, *TRB 93rd Annual Meeting Compendium of Papers*, Paper #14-5077, 2014. Citation at http://trid.trb.org/view/1289749
From the abstract: [T]he authors make initial estimates of the range of energy impacts possible due to widespread adoption of AVs. To do this, the authors collect available estimates for the energy impacts of ten potential effects of AVs. The authors then use a modified Kaya Identity approach to estimate the overall range of possible effects. Depending on the specific effects that come to pass, there is a wide range of potential energy outcome scenarios. Therefore, widespread AV deployment can lead to dramatic fuel savings, but has the potential for unintended consequences.

The Future of Fully Automated Vehicles: Opportunities for Vehicle- and Ride-Sharing, with Cost and Emissions Savings, Daniel Fagnant and Kara Kockelman, Southwest Region University Transportation Center, August 2014.
https://static.tti.tamu.edu/swutc.tamu.edu/publications/technicalreports/600451-00081-1.pdf
From the abstract: This work simulates a fleet of SAVs [shared automated vehicles] operating within the city of Austin, using Austin's transportation network and travel demand flows. This model incorporates dynamic ride-sharing (DRS), allowing two or more travelers with similar origins, destinations and departure times to share a ride. Model results indicate that each SAV could replace around 10 conventionally-owned household vehicles while serving over 56,000 person-trips. SAVs' ability to relocate while unoccupied between serving one traveler and the next may cause an increase of 4-8% more travel; however, DRS can result in reduced overall VMT, given enough SAV-using travelers willing to ride-share. SAVs should produce favorable emissions outcomes, with an estimated 16% less energy use and 48% lower volatile organic compound (VOC) emissions, per person-trip formerly served by a household vehicle.

"Environmental and Energy Impacts of Automated Electric Highway Systems," Steven Lavrenz and Konstantina Gkritza, *Journal of Intelligent Transportation Systems*, Vol. 17, No. 3, pages 221-232, August 2013.
Citation at http://trid.trb.org/view/1266604
From the abstract: This article proposes a methodology that can be applied to evaluate the environmental and energy impacts of a de novo technology, the automated electric highway systems (AEHS). The authors used the Motor Vehicle Emission Simulator (MOVES) program to estimate the impacts on emissions and energy use associated with a hypothetical implementation of this technology on the Interstate 70 corridor in Missouri during the period 2011-2040. The estimation results suggest that application of AEHS on the study corridor would decrease fossil fuel energy use by more than 25%, while emissions would decrease by up to 27%, depending on the pollutant being considered. A sensitivity analysis was also performed, in order to assess the impact of different demand estimates for the system; a 10% reduction in AEHS vehicle miles traveled would have an effect of 5% or less on the criteria of interest.

Impact on Vehicle Miles Traveled

Research in Progress: Estimating Safety Benefits and Costs and Changes in Vehicle Miles Traveled from Vehicle Automation, Technologies for Safe and Efficient Transportation (national University Transportation Center for safety), project start date: January 2016, expected completion date: January 2017. (The web site does not provide a link to the completed report.) Project description at http://utc.ices.cmu.edu/utc/projectitem.asp?ID=193

From the project description: This policy research project would address two significant impacts of vehicle automation: (1) Do the safety benefits outweigh the technology costs for partial automation systems now being introduced? This task will use current motor vehicle offerings and insurance institute records. If new, partial automation technology is cost-effective, then it is highly likely that improved technology will be even more desirable. (2) What would be the bounds on the increases in VMT that might occur with driverless vehicles available for use? A large increase in VMT could result in many current transportation systems facing challenges in providing efficient and reliable service to users, while a decrease in VMT could have implications on land use. As vehicles become more automated, there are varying levels of crash avoidance technologies and potential safety benefits. During this transition period, additional VMT by automated and non-automated vehicles will likely have an impact on crash risk and road safety. This task will use New York City (NYC) yellow taxicab trip and fare data, analytical models and expert elicitation to assess the overall likely impacts to current light duty VMT from vehicle automation.

An Assessment of Autonomous Vehicles: Traffic Impacts and Infrastructure Needs— Final Report, Texas Department of Transportation, March 2017.
https://library.ctr.utexas.edu/ctr-publications/0-6847-1.pdf
From the abstract: NHTSA's [National Highway Traffic Safety Administration's] four-level taxonomy for automated vehicles was used to classify smart driving technologies and infrastructure needs. The project used surveys to analyze and gain an understanding of the U.S. general public's perception towards such technologies and their willingness to adopt such technologies. Respondents were asked several anticipatory questions including their technology preferences (buying/selling their vehicles or simply adding new technologies to their current vehicles), and their comfort with and willingness to pay for connected and autonomous vehicles (CAVs). The team found that advanced automation technologies are not yet popular.

This research report also describes the potential crash, congestion and other impacts of CAVs in Texas, and provides initial monetary estimates of those impacts, at various levels of market penetration. Our findings indicate that CAVs will lead to increased vehicle miles traveled (VMT) because, essentially, drivers experience falling travel time burdens. Their values of travel time that make using a vehicle "costly" tend to decrease because they are more comfortable heading to more distant locations and those unable to drive themselves, such as the handicapped, can now safely travel.

"Analysis of the Impacts of CAV Technologies on Travel Demand," Joshua Auld, Vadim Sokolov and Thomas Stephens, *TRB 96th Annual Meeting Compendium of Papers*, Paper #17-06453, 2017.
Citation at http://trid.trb.org/view/1439577
From the abstract: [I]n this study the authors use an advanced transportation systems simulation model, POLARIS, which includes co-simulation of travel behavior and traffic flow, to study potential impacts of several connected and automated vehicle technologies at the regional-level. The authors have analyzed various market penetration levels and changes in

travel time sensitivity to determine a potential range of VMT impacts from various CAV technologies.

"Autonomous Vehicles: Hype and Potential," Peter Calthorpe and Jerry Walters, *Public Square: A CNU Journal*, September 2016.
http://www.fehrandpeers.com/wp-content/uploads/2017/03/CNU-Article-Autonomous-Rapid-Transit.pdf
The authors' conclusions, which begin on page 8 of the PDF of this online newsletter article, include the following:

- Standard private vehicles and trucks must be eliminated before automated (or autonomous) vehicles (AVs) can function at full efficiency on local streets. Until then, AVs will lead to increased miles driven—one-third more for personal AV and up to twice as many for unshared AV taxis.

- Personal AV use will heighten suburban sprawl as longer trips become more tolerable.

- In the short term and the long term, the best application of AV technology is a network of autonomous rapid transit (ART) lines combined with high-capacity metro transit systems. This will avoid degradation of AV performance due to mixed flow, and will likely attract users to reduce their private auto use. This can then easily evolve into complete ART districts in which private cars are eliminated.

"Shifts in Long-Distance Travel Mode Due to Automated Vehicles: Statewide Mode-Shift Simulation Experiment and Travel Survey Analysis," Jeffrey LaMondia, Daniel Fagnant, Hongyang Qu, Jackson Barrett and Kara Kockelman, *Transportation Research Record 2566*, pages 1-10, 2016.
Citation at http://trid.trb.org/view/1393447
From the abstract: This study analyzed travel surveys and then developed a statewide simulation experiment of long-distance travel to anticipate the impact of AVs on long-distance travel choices. The research explored the Michigan State 2009 Long-Distance Travel Survey and estimated a long-distance trip generation model and a modal-agnostic long-distance mode-choice model. These models were applied in a statewide simulation experiment in which AVs were introduced as a new mode with lower perceived travel time costs (via lowered values of travel time en route) and higher travel costs (to reflect the initially high price of complete vehicle automation). This experiment highlighted the potential shifts in mode choices across different trip distances and purposes. For travel of less than 500 mi[les], AVs tended to draw from the use of personal vehicles and airlines equally. Airlines were estimated to remain preferred for distances greater than 500 mi[les] (43.6% of trips greater than 500 mi[les] were by air, and 70.9% of trips greater than 1,000 mi[les] were by air). Additionally, at certain AV travel time valuations, travel cost was not a significant factor. The findings showed that as the perceived travel time benefits from hands-free travel rose, monetary costs became less important.

Potential Impact of Self-Driving Vehicles on Household Vehicle Demand and Usage, Brandon Schoettle and Michael Sivak, University of Michigan Transportation Research Institute, February 2015.
http://www.driverlesstransportation.com/wp-content/uploads/2015/02/UMTRI-2015-3.pdf
From the abstract: In this report we present an analysis of the potential for reduced vehicle ownership within households based on sharing of completely self-driving vehicles that employ a "return-to-home" mode, acting as a form of shared family or household vehicle. An examination of the latest U.S. National Household Travel Survey (NHTS) data shows a general lack of trip overlap between drivers within a majority of households, opening up the possibility for a

significant reduction in average vehicle ownership per household based on vehicle sharing. This reduction in ownership and an accompanying shift to vehicle sharing within each household, in the most extreme hypothetical scenario, could reduce average ownership rates by 43%, from 2.1 to 1.2 vehicles per household. Conversely, this shift would result in a 75% increase in individual vehicle usage, from 11,661 to 20,406 annual miles per vehicle. (This increase in mileage does not include the additional miles that would be generated during each "return-to-home" trip.) However, given the number of current unknowns regarding sufficient gaps between trips, future self-driving-vehicle implementation, self-driving-vehicle acceptance, and possible vehicle-sharing strategies within households, these results serve only as an upper-bound approximation of the potential for household sharing of completely self-driving vehicles.

"Bounding the Potential Increases in Vehicles Miles Traveled for the Non-Driving and Elderly Populations and People with Travel-Restrictive Medical Conditions in an Automated Vehicle Environment," Corey Harper, Sonia Mangones, Chris Hendrickson and Constantine Samaras, *TRB 94th Annual Meeting Compendium of Papers*, Paper #15-1609, 2015.
Citation at http://trid.trb.org/view/1337190

From the abstract: This paper estimates the impact of a fully automated vehicle environment on the total vehicle miles traveled (VMT) by the current U.S. population 19 and older due to an increase in mobility from the non-driving and elderly populations and people with travel-restrictive medical conditions. The primary source of data for this project is the 2009 National Household Transportation Survey (NHTS), which provides information on current travel characteristics of the U.S. population. The changes to the total VMT are estimated by examining three possible demand wedges. In demand wedge one, the assumption made is that non-drivers would travel as much as the drivers within each age group and gender. Demand wedge two assumes that the driving elderly without medical conditions will travel as much as young adults (ages 19-64) within each gender. Demand wedge three makes the assumption that drivers with medical conditions will travel as much as the drivers without medical conditions within each age group and gender in a fully autonomous and connected vehicle environment. The combination of the results from all three demand wedges represents an upper bound of 297 billion miles or a 12% increase in overall VMT. Since traveling has other costs than driving effort, this estimate serves to bound the potential increase from these populations to inform the scope of the challenges, rather than forecast specific VMT scenarios.

Equity, Public Health and Social Impacts

"Public Health, Ethics and Autonomous Vehicles," Janet Fleetwood, *American Journal of Public Health*, Vol. 107, No. 4, pages 532-537, April 2017.
http://ajph.aphapublications.org/doi/full/10.2105/AJPH.2016.303628
The author of this journal article offers this call to action:

> Public health leaders can focus on 4 pragmatic areas with ethical impact, including (1) advocating transparent and collaborative discussion of public health issues related to autonomous vehicles, starting with the forced-choice algorithms under development by manufacturers; (2) expanding the public's awareness of the ideals of public health and ethical issues relevant to autonomous vehicles; (3) facilitating the inclusion of broad perspectives—including the historically disenfranchised—in the discussion of issues, including community input into when, where and how autonomous vehicles are tested and deployed; and (4) ensuring that rational, ethically justifiable regulations are developed consistently across states, codified by the appropriate government agency, funded appropriately, and implemented, monitored and assessed effectively.

Can We Advance Social Equity with Shared, Autonomous and Electric Vehicles?, Stuart Cohen and Sahar Shirazi**,** Policy Brief, Institute of Transportation Studies, February 2017.
http://www.transformca.org/transform-report/can-we-advance-social-equity-shared-autonomous-and-electric-vehicles
This policy brief addresses how autonomous vehicles could benefit:

- Low-income communities.

- Mobility-challenged people, including people with disabilities, seniors and youth.

- Other historically disadvantaged communities, including people of color, immigrant communities (including those with language barriers) and rural communities.

"Equity, Safety and Privacy in the Autonomous Vehicle Era," Vasant Dhar, *Computer*, Vol. 49, No. 11, pages 80-83, November 2016.
https://www.computer.org/csdl/mags/co/2016/11/mco2016110080.pdf
In this article's conclusion, the author notes that "[d]espite the fine-grained nature of the data they collect, onboard vehicular systems need not expose drivers to serious privacy risks as long as we regulate the use of such data carefully. Technical and legal solutions are available to anonymize the data and prevent its unauthorized use. Just as wearable devices are enabling individuals to improve their health and fitness, vehicles could become yet another rich source of information for personal knowledge discovery by the 'quantified self,' while also making the world a safer place for everyone to navigate."

Environmental Justice Considerations for Connected and Automated Vehicles, Federal Highway Administration, December 2016.
http://www.fhwa.dot.gov/environment/environmental_justice/publications/cv_av/cvav.pdf
This publication examines the risks and potential benefits of CAVs as they relate to environmental justice (EJ) populations. The abstract cautions that "[a]s policy discussions, planning, and implementation for CVs [connected vehicles] and vehicle automation proceed, decision-makers should consider equity concerns and pursue policies to ensure that EJ populations do not experience disproportionately high and adverse human health or environmental effects."

Roadway Impacts

Research in Progress: Strategic and Tactical Guidance for the Connected and Autonomous Vehicle Future, Indiana Department of Transportation, project start date: January 2017, expected completion date: June 2018.
Project description at https://trid.trb.org/view/1435568
From the project description: Automated vehicle (AV) and [c]onnected vehicle (CV) technologies are rapidly maturing and the timeline for their wider deployment is currently uncertain. The objectives of this research are: (1) Synthesize the existing state of practice and how other state agencies are addressing the pending transition to AV/CV environment; (2) Estimate the impacts of AV/CV environment within the context of (i) traffic operations—impact of headway distribution and traffic signal coordination; (ii) Traffic control devices and (iii) roadway safety in terms of intersection crashes and (3) provide a strategic roadmap for INDOT in preparing for and responding to potential issues.

Research in Progress: Transitioning Roadways to Accommodate Connected and Automated Vehicles: A Pennsylvania Case Study, Technologies for Safe and Efficient Transportation, project start date: January 2017, expected completion date: July 2018.
Project description at https://trid.trb.org/View/1482039
From the abstract: For this research project the team will assess options for the Pennsylvania Turnpike to begin transitioning towards accommodating CAVs, using toll log, crash, and traffic data for this roadway. The project team will identify roadway sections that have high crash frequencies, consistent congestion, and available right-of-way to enable adaptive designs for automation. These include but are not limited to: innovative roadway sections with reduced-width CAV-only lanes, vehicle-to-infrastructure prioritization plans, and sections where CAVs and traditional vehicles can most safely interact. The recommendations resulting from this work will also be applicable to other existing roadways around the country.

Blueprint for Autonomous Urbanism, Module 1, Designing Cities Edition, National Association of City Transportation Officials, Fall 2017.
Print version available at https://nacto.org/wp-content/uploads/2017/11/BAU_Mod1_raster-sm.pdf; web version available at https://nacto.org/publication/bau/
From the introduction:

> This Blueprint outlines a vision for cities in a future where automated transportation is both accepted and widespread as part of the built environment. It is a human-oriented vision for the potential of city streets, intersections and networks—one in which automation can serve the goals of safety, equity, public health and sustainability.

This modular blueprint, available in print and web versions, "addresses some of the most pressing issues city transportation agencies face today but acknowledges those issues will vary by city and over time. The modular approach is an attempt to lay the groundwork in a field that moves rapidly. We will be build on this vision as technology advances."

Developing "Highway Capacity Manual" Capacity Adjustments for Agency Connected and Autonomous Vehicle Operational Planning Readiness under Varying Levels of Volume and Market Penetration, Study Number TPF-5(371), Transportation Pooled Fund Program, National Cooperative Highway Research Program, July 2017.
Project web site at http://www.pooledfund.org/Details/Study/623
From the project description: The research objectives of this project are to develop the highway capacity adjustments for CAVs at different levels of volume and market penetration in order to

adapt the use of HCM [Highway Capacity Manual] in analyzing CAV applications. … The expected products of this research are highway capacity adjustment lookup tables and figures for different facilities (freeway, arterials) at different levels of CAV market penetration. This project is designed to address the limitations identified with respect to the CAV effects in HCM analysis procedures. … This project will benefit public agencies to accommodate highway capacity related analysis under the impacts of CAV for different levels of volumes and market penetrations. Specifically, it will inform agencies about how CAV market penetration will affect capacity leading to better informed investment decisions in area freeways, new roundabouts and signals, and safety projects.

"Assessing the Potential Impacts of Connected Vehicles: Mobility, Environmental and Safety Perspectives," Arash Olia, Hossam Abdelgawad, Baher Abdulhai and Saiedeh N. Razavi, *Journal of Intelligent Transportation Systems*, Vol. 20, No. 3, pages 229-243, May 2016. Citation at http://trid.trb.org/view/1407274
From the abstract: To assess the benefits of CVs, a modeling framework is developed based on traffic microsimulation for a real network located in the city of Toronto, Canada, to mimic communication between enabled vehicles. In this study, the authors examine the effects of providing real-time routing guidance and advisory warning messages to CVs. In addition, to take into account the rerouting in nonconnected vehicles (non-CVs) in response to varying sources of information such as apps, global positioning systems (GPS), variable message signs (VMS), or simply seeing the traffic back up, the impact of fraction of non-CV vehicles was also considered and evaluated. Therefore, vehicles in this model are divided into 25 uninformed/unfamiliar not connected (non-CV), 7 informed/familiar but not connected (non-CV) that get updates infrequently every 5 minutes or so (non-CV), and 34 connected vehicles that receive information more frequently (CV). The results demonstrate the potential of connected vehicles to improve mobility, enhance safety, and reduce greenhouse gas emissions (GHGs) at the network-wide level. The results also show quantitatively how the market penetration of connected vehicles proportionally affects the performance of the traffic network. While the presented results are pertinent to the specifics of the road network modeled and cannot be generalized, the quantitative figures provide researchers and practitioners with ideas of what to expect from vehicle connectivity concerning mobility, safety, and environmental improvements.

Effects of Next-Generation Vehicles on Travel Demand and Highway Capacity, FP Think Working Group, Fehr & Peers, February 2014.
http://www.fehrandpeers.com/wp-content/uploads/2015/07/FP_Think_Next_Gen_Vehicle_White_Paper_FINAL.pdf
As the executive summary indicates, this white paper "assesses the most likely effects of autonomous vehicles (AVs) on traffic generation, highway capacity, and congestion over time as AVs come to represent a greater percentage of the vehicles on the road."

From page 3 of the white paper (page 6 of the PDF):

> Favorable effects on the efficiency of the roadway network will vary by facility type [and] will take several decades to produce a 50% increase in operating efficiency and capacity utilization. Concurrently, improved driver experience and the availability of robo-chauffeuring for those who would otherwise not be permitted to drive may increase VMT per capita by as much as 35%, off-setting much of the efficiency gain. Although the net operational improvements to streets and highways would not significantly reduce the need to expand infrastructure to keep pace with population growth, the bottom-line benefits of AVs on the road are most likely to take the form of improved mobility for all, increased safety, reduced incident-related congestion and reduced environmental and social costs per vehicle mile traveled.

Other Impacts

Land Use and Livability

Anticipated Research: Impact of Transformational Technologies on Land Uses, NCHRP Project 08-117, anticipated in 2018. (*From the web site:* This project has been tentatively selected and a project statement (request for proposals) is expected in July 2017.)
Project description at http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=4364
From the project description: Several transformational technologies are coming together to profoundly influence transportation in cities and the broader impact of transportation on city services and operations. These beneficial technologies include mobility-on-demand (MODs) services, shared vehicles, connected and automated vehicles (CAVs), alternative-fuel vehicles (AFVs), smart cities and communities, and big data analytics. … The objective of this research is to document potential and likely changes in site selection and demand for retail, office, distribution, production, housing, and parking land due to development of transformational technologies. The research should give broad consideration to transformational technologies, but may focus on three to five technologies likely to be particularly influential over a period of one to two decades. The research should consider implications for urban development patterns as well as real estate markets and issues of government policy as related to personal travel and freight transportation.

Land Use and Transportation Policies, Marco Anderson, Nico Larco, Giovanni Circella and Lisa Aultman-Hall, Policy Brief, 3 Revolutions Policy Initiative, Institute of Transportation Studies, University of California, Davis, April 2017.
https://3rev.ucdavis.edu/wp-content/uploads/2017/04/3R.LandUse.Final_.pdf
This policy brief highlights key issues for land use and transportation planning. Policy recommendations begin on page 2 of the policy brief and include the following:

1. The best policies to mitigate autonomous vehicle-induced sprawl are many of the same policies currently being implemented to mitigate traditional sprawl.

2. The most important policy levers to mitigate against more sprawl and environmental damage will be pricing.

3. Operationalizing a fix-it-first policy will allow regional transportation agencies to make best use of transportation investments and prevent sprawl.

4. Replacing federal, state and local auto-oriented transportation engineering with multimodal integrated transportation policies will encourage the environmental and community benefits of the three revolutions.

5. Reforming state, local and regional land-use policies to support the three revolutions will require reform to development and redevelopment practices and increased public private partnerships.

Also discussed are opportunities for future research (see page 6).

"Autonomous Vehicles and Commercial Real Estate," Jason Henderson and Jason Spencer, *Cornell Real Estate Review*, Vol. 14, No. 1, pages 44-55, 2016.
http://scholarship.sha.cornell.edu/cgi/viewcontent.cgi?article=1152&context=crer
This Cornell University publication identifies the following impacts associated with the use of AVs:

- AVs are likely to yield much greater travel efficiency because they can operate more efficiently, and the total vehicle count on the road may decrease since AVs could alleviate the need for single ownership and usage.

- AVs use roadways more efficiently, allowing for the narrowing of roads and conversion of extra space, leading to the following observation:

   The additional space in front of buildings and in-between two-way boulevards could provide for a range of usage options such as widened sidewalks, tree-lining, parking, retail seating, and stormwater runoff filtration.

- With narrower road widths, the amount of impervious surfaces is decreased, reducing the need for stormwater runoff treatment systems and reducing the urban heat island effect, which leads to a lower demand for air conditioning and electricity.

- Lower-density areas and suburbs may see the greatest impact; central business districts may see little impact.

Last-Mile Service

"Shared Autonomous Vehicles as a Sustainable Solution to the Last Mile Problem: A Case Study of Ann Arbor-Detroit Area," Aditi Moorthy, Robert De Kleine, Gregory Keoleian, Jeremy Good and Geoff Lewis, *SAE International Journal of Passenger Cars—Electronic and Electrical Systems*, Vol. 10, No. 2, March 2017.
Citation at http://trid.trb.org/view/1461568
From the abstract: This paper analyzes the implications of a shared autonomous vehicle (AV) taxi system providing last mile transit services in terms of environmental, cost, and performance metrics. Conventional public transit options and a hypothetical last-mile shared autonomous vehicle (SAV) system are analyzed for transit between Ann Arbor and Detroit Wayne County Airport for life cycle energy, emissions, total travel time, and travel costs. In the case study, energy savings from using public transit options with AV last mile service were as high as 37% when compared to a personal vehicle option. Energy and greenhouse gas burdens were very sensitive to vehicle powertrain and ridership parameters. The results suggest that an AV taxi service providing last-mile transit services could enhance the sustainability of transit by influencing a mode shift from private modes to public modes of transit. Wait times associated with public transit options, as well as high AV technology costs, could be obstacles for a last mile service.

Travel Behavior

"Developing a Platform to Analyze Behavioral Impacts of Connected Automated Vehicles at the National Level," Ramin Shabanpour, Joshua Auld, Abolfazl (Kouros) Mohammadian, and Thomas Stephens**,"** *TRB 96th Annual Meeting Compendium of Papers*, Paper #17-06283, 2017.
Citation at http://trid.trb.org/view/1439507
From the abstract: This study aims to develop a methodological framework that utilizes multiclass data fusion and data transferability techniques, which uses data and models from a smaller geographical area (e.g., Chicago and Detroit) to generate the needed disaggregate data in a larger scale (e.g., national level). This framework is able to perform a comprehensive examination on the impacts of CAV in transportation networks. To achieve this goal, an advanced transportation systems simulation model, POLARIS, which simulates both travel behavior and traffic flow, is used to estimate the potential impacts of CAV technologies at a regional-level. The rich output of CAV scenario analysis in POLARIS framework includes

information on person-level and household-level socio-demographic attributes as well as detailed activity-travel patterns. Transferable variables such as total trip rates and travel times are also derived from POLARIS. Following that, the authors use Exhaustive CHAID decision tree models for each transferable variable to cluster people into several homogeneous groups through which various types of lifestyles are captured. The best-fitted statistical distribution for each of the final decision tree clusters is then determined to analyze the specific behavior of members of each cluster toward transferable variables. Finally, using an artificial neural network model, cluster membership rules and travel statistics are transferred to the national level to develop a validated baseline national platform for analyzing connected automated vehicles scenarios. The platform that is capable of transferring travel behavior to national level with high level of accuracy will be utilized to test various policies and scenarios that may affect the use of CAV and their national impacts.

"Towards an Understanding of the Travel Behavior Impact of Autonomous Vehicles," Johanna P. Zmud and Ipek N. Sener, *Transportation Research Procedia*, Vol. 25, pages 2504-2523, 2017.
Citation at http://trid.trb.org/view/1470694
From the abstract: This study gathered empirical evidence on adoption patterns of self-driving vehicles, people's likely use of them, and how that might influence amount of travel, mode choice, auto ownership, and other travel behaviour decisions. Because self-driving vehicles are not yet on the market, a car technology acceptance model was applied to understand adoption and use. Researchers implemented a two-stage data collection effort. An online survey was conducted with 556 residents of metropolitan Austin to determine intent to use. Based on results, four "intent to use" categories were determined: (1) extremely unlikely = Rejecters (18%); (2) somewhat unlikely = Conservatives (32%); (3) somewhat likely = Pragmatists (36%); (4) extremely likely = Enthusiasts (14%). Individuals with a higher level of intent to use have any physical conditions that prohibit them from driving; use technology—smartphone, text messaging, Facebook, transportation apps—and are not concerned with data privacy about using online technology; think using self-driving vehicles would be fun, decrease accident risk, and easy to become skilful at using; and believe people whose opinions are valued would like using them. Among those who indicated intent to use, qualitative interviews were conducted to ascertain the impact on their travel behaviour.

Planning, Modeling and Evaluation

Planning

Impacts of Connected Vehicles and Automated Vehicles on State and Local Transportation Agencies—Task-Order Support, NCHRP Project 20-102. (This is an ongoing project with subtasks described below.)
Project description at http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=3824
The objectives of this wide-ranging NCHRP project "are to (1) identify critical issues associated with connected vehicles and automated vehicles that state and local transportation agencies and AASHTO will face, (2) conduct research to address those issues, and (3) conduct related technology transfer and information exchange activities."

Below are the individual tasks associated with the broader NCHRP project:

Policy and Planning Actions to Internalize Societal Impacts of CV and AV Systems into Market Decisions, NCHRP Project 20-102(01)
Project description at
http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=3934

Impacts of Regulations and Policies on CV and AV Technology Introduction in Transit Operations, NCHRP Project 20-102(02)
Project description at
http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=3935

Challenges to CV and AV Application in Truck Freight Operations, NCHRP Project 20-102(03)
Project description at
http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=3936
Strategic Communications Plan for NCHRP Project 20-102, NCHRP Project 20-102(05)
Project description at
http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=4005

Road Markings for Machine Vision, NCHRP Project 20-102(06)
Project description at
http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=4004

Implications of Automation for Motor Vehicle Codes, NCHRP Project 20-102(07)
Project description at
http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=4006

Dedicating Lanes for Priority or Exclusive Use by CVs and AVs, NCHRP Project 20-102(08)
Project description at
http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=4007

Providing Support to the Introduction of CV/AV Impacts into Regional Transportation Planning and Modeling Tools, NCHRP Project 20-102(09)
Project description at
http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=4008

Cybersecurity Implications of CV/AV Technologies on State and Local Transportation Agencies, NCHRP Project 20-102(10)
Project description at
http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=4254

Summary of Existing Studies on the Effects of CV/AV on Travel Demand, NCHRP Project 20-102(11)
Project description at
http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=4255

Business Models to Facilitate Deployment of CV Infrastructure to Support AV Operations, NCHRP Project 20-102(12)
Project description at
http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=4256

Planning Data Needs and Collection Techniques for CV/AV Applications, NCHRP Project 20-102(13)
Project description at
http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=4257

Data Management Strategies for CV/AV Applications for Operations, NCHRP Project 20-102(14)
Project description at
http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=4258

Understanding the Impacts of the Physical Highway Infrastructure Caused by the Increased Prevalence of Advanced Vehicle Technologies, NCHRP Project 20-102(15)
Project description at
http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=4377

The project description also notes that "NCHRP Project 20-24(98) has developed a draft research roadmap for addressing CV/AV issues. The panel for NCHRP Project 20-102 is responsible for maintaining this roadmap and will be selecting tasks from it to carry out. Tasks may be rescoped, added, or deleted from the roadmap at the discretion of the panel." See Related Resource below for a citation for the research roadmap.

Related Resource:

NCHRP 20-24(98): Connected/Automated Vehicle Research Roadmap for AASHTO, Steven E. Shladover and Douglas Gettman, NCHRP Project 20-24(98), Deliverable 2, June 2015.
http://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP20-24(98)_RoadmapTopics_Final.pdf
This research roadmap includes descriptions of 23 proposed projects. Each description includes a problem statement, task outline, anticipated deliverables, resource estimate and an assessment of the urgency of the topic. Topics are grouped in four categories: institutional and policy issues; infrastructure design and operations; planning issues; and modal applications (transit and trucking).

NCHRP Report 845: Advancing Automated and Connected Vehicles: Policy and Planning Strategies for State and Local Transportation Agencies, Johanna Zmud, Ginger Goodin, Maarit Moran, Nidhi Kalra and Eric Thorn, 2017.
https://download.nap.edu/cart/download.cgi?record_id=24872
http://www.trb.org/Main/Blurbs/176418.aspx
From the foreword:

> In NCHRP Project 20-102(01), the Texas A&M Transportation Institute, RAND Corporation, Southwest Research Institute, and the University of Utah identified and described mismatches between potential societal impacts and factors that influence private-sector decisions on CV and AV technologies. Policy and planning actions that might better align these interests were then identified. After meeting with the project oversight panel to identify the most promising actions, the research team conducted in-depth evaluations of the feasibility, applicability and impacts of 18 strategies.

A discussion of policy and planning strategies begins on page 3 of the report (page 12 of the PDF):

> Society could benefit if state, regional and local governments were to implement policy and planning strategies to (a) internalize these externalities in decision making by consumers and (b) reduce negative societal effects and increase positive societal effects of AVs and CVs, regardless of whether they are internal or external to market decisions. Both types of strategies would result in better societal outcomes.

The report then presents the 18 strategies, organized by desired outcome. Researchers assessed the viability of each strategy using the following criteria: effectiveness and efficiency in achieving the desired outcome, political acceptability, operational feasibility, geographic impact, who would implement and hurdles to implementation. Below are the outcomes under which the 18 strategies are categorized:

- To mitigate safety risks through testing, training and public education.
- To encourage shared AV use.
- To address liability issues that may impact market development.
- To enhance safety, congestion and air quality benefits by influencing market demand.

Transportation Planning Implications of Automated/Connected Vehicles on Texas Highways, Thomas Williams, Jason Wagner, Curtis Morgan, Kevin Hall, Ipek Sener, Gretchen Stoeltje and Hao Pang, Texas Department of Transportation, April 2017.
https://static.tti.tamu.edu/tti.tamu.edu/documents/0-6848-1.pdf
From the abstract:

> This research project was focused on the transportation planning implications of automated/connected vehicles (AV/CVs) on Texas highways. The research assessed how these potentially transformative technologies can be included in transportation planning to assist the decision-making process.

The research project included the following elements:

- A literature search that examined existing CAV technologies and explored future technologies.

- An examination of potential changes that CAVs may have on travel behavior, urban form and other aspects of the transportation system.

- A review of the potential effects of automation on commercial vehicle and freight transportation.

- A review of the impact of CAVs on travel modeling, including experimental model runs using a trip-based model from the Austin, Texas, region.

- A statewide web-based behavioral preferences survey and stakeholder workshops held in spring 2016.

3 Revolutions Policy Briefs, 3 Revolutions Policy Initiative, Institute of Transportation Studies, University of California, Davis, 2017.
https://3rev.ucdavis.edu/about/ and https://3rev.ucdavis.edu/policybriefs/
From the web site:

> The rapid adoption of shared mobility services and electric vehicles, coupled with the prospect of driverless vehicles, has the potential to radically transform how people and goods move in advanced and emerging economies. Three revolutions in transportation— shared mobility, electrification and autonomous vehicles—will fundamentally change transportation around the world. Rigorous research and impartial policy analysis are urgently needed to understand the impacts of these transportation revolutions, and to guide industry investments and government decision-making.

The web site also describes the origins of the policy briefs:

> The 3 Revolutions Policy Briefs reflects a body of work that was started at the 3 Revolutions Conference in November 2016, where leaders from across the United States and Europe came together to discuss the future of transportation. During the conference attendees discussed topics that were developed into a series of policy briefs to introduce policy challenges, recommendations and research needs on a variety of topics.

The following policy briefs are available at the 3 Revolutions web site:

Active Transportation in an Era of Sharing, Electrification and Automation (February 2017)
https://3rev.ucdavis.edu/wp-content/uploads/2017/03/3R.Active.InDesign.Final_.pdf

Capturing the Climate Benefits of Autonomous Vehicles (February 2017)
https://3rev.ucdavis.edu/wp-content/uploads/2017/03/3R.Climate.Indesign.Final_.pdf

Can We Advance Social Equity With Shared, Autonomous and Electric Vehicles? (February 2017)
https://3rev.ucdavis.edu/wp-content/uploads/2017/03/3R.Equity.Indesign.Final_.pdf

Governance: Who's in Charge Here? (February 2017)
https://3rev.ucdavis.edu/wp-content/uploads/2017/03/3R.Governance.Indesign.Final_.pdf

Three Transportation Revolutions: Synergies With Transit (February 2017)
https://3rev.ucdavis.edu/wp-content/uploads/2017/06/3R.Transit.Final_-1.pdf

See pages 12 and 22 of this Preliminary Investigation for 3 Revolutions policy briefs on GHG emissions and land use, respectively.

Modeling

Travel Modeling in an Era of Connected and Automated Transportation Systems: An Investigation in the Dallas-Fort Worth Area, Data-Supported Transportation Operations & Planning Center, The University of Texas at Austin, February 2017.
http://ctr.utexas.edu/wp-content/uploads/122.pdf
This three-part report, commissioned by the North Central Texas Council of Governments, considers how travel modeling can be used in connection with CAVs:

- Part I examines the state of technology for both CAVs and "provides evidence that the discrete technologies to enable both vehicle capabilities are nearing market readiness." This section of the report contrasts the two technologies and examines policy, privacy and security questions.

- Part II concludes "that there will likely be decades of mixed use between AVs and human-driven vehicles. In addition, this section discusses existing adoption predictions from private consultants and academics, provides adoption estimates of CAVs based on adoption rates of similar technologies in the past, and proposes assumptions for three planning scenarios."

- Part III describes 112 proposed potential planning scenarios that reflect the wide range of potential CAV impacts. As the authors note, "[t]he proposed scenarios are built based on the analysis of possible adoption timelines for vehicle automation and connectivity, and consider the impact of additional behavioral and technological factors, using existent regional planning methodologies. The limitations of traditional modeling tools may limit the observed impacts of CAVs, which can motivate the exploration of more advanced tools such as activity-based models and dynamic traffic assignment."

"Modelling the Impact of Automated Driving—Private Autonomous Vehicle Scenarios for Germany and the U.S.," Lars Kröger, Tobias Kuhnimhof and Stefan Trommer, *European Transport Conference 2016: Strands*, 2016.
Citation at http://trid.trb.org/view/1436860
From the abstract: The paper presents results from modelling travel behavior impacts of introducing AVs into the private car fleet. In order to model such a 2035 scenario, the authors combined a vehicle technology diffusion model and an aspatial travel demand model and applied this to Germany and the USA. Differentiating by passenger car segment, the authors introduce AVs among the newly registered vehicles from 2021 onward assuming an s-shaped market-take-up until 2035. By then, 50% of the new vehicles and 25% of the passenger car fleet are projected to be AVs. Again differentiating by segment and age, the AVs can be found among specific driver groups. In addition the authors assume that AVs are owned by mobility impaired travelers who did not have the option to drive previously. Subsequently, the authors use a travel demand model consisting of trip generation, distance choice and mode choice to forecast travel by different traveler groups and by car availability (no car, conventional car, AV). For modelling the impact of AVs compared to conventional cars, the authors reduced access/egress times due to quicker parking/valet parking and they reduced values of car travel time savings for travelers with AVs. While the model results overall conform to expectation the impact of AVs on travel behavior are not large: There is a ~5% increase in VMT for both Germany and the USA, resulting from somewhat longer trips combined with slight modal shifts from other modes towards the car. These results have important implications: If the regulatory framework for AVs is such that a private AV scenario is the most likely development, AVs are

not likely to revolutionize travel. AVs will change travel behavior—but their impact might be marginal compared to other external factors.

"Using an Activity-Based Model to Explore Possible Impacts of Automated Vehicles,"
Suzanne Childress, Brice Nichols, Billy Charlton and Stefan Coe, Presented at the TRB 94th Annual Meeting, January 2015.
https://psrc.github.io/attachments/2014/TRB-2015-Automated-Vehicles-Rev2.pdf
From the abstract: This research uses the Seattle region's activity-based travel model to test a range of travel behavior impacts from AV technology development. The existing model was not originally designed with automated vehicles in mind, so some modifications to the model assumptions are described in areas of roadway capacity, user values of time, and parking costs. Larger structural model changes are not yet considered. Results of four scenario tests show that improvements in roadway capacity and in the quality of the driving trip may lead to large increases in vehicle-miles traveled, while a shift to per-mile usage charges may counteract that trend. Travel models will need to have major improvements in the coming years, especially with regard to shared-ride, taxi modes, and the effect of multitasking opportunities, to better anticipate the arrival of this technology.

Assessing the Long-Term Effects of Autonomous Vehicles on Mode Choice Behavior: A Speculative System Dynamics Approach, Wolfgang Gruel and Joseph Stanford, *European Transport Conference 2015: Strands*, 2015.
Citation at http://trid.trb.org/view/1371889
From the abstract: Using a system dynamics model, the authors investigate how autonomous operation could affect the attractiveness of traveling by car, how this in turn would affect mode-choice, and how changes in mode-choice would affect the broader transportation system. The model explores four speculative scenarios, using a generic model of an urban area, based on an existing model of Cambridge, Massachusetts, which was developed with VensimPLE software. The results affirm the expected benefits of autonomous vehicles—if mobility behavior does not change significantly. However, the model also shows that autonomous vehicles offer new behavioral opportunities that lead to undesired results like more congestion and more emissions. Finally, the authors discuss potential policy interventions to encourage positive outcomes, and identify additional questions and avenues for research. The paper extends the view on autonomous vehicles and provides insights for policy-makers, transportation and urban planners, vehicle manufacturers, and public transit operators.

"The Travel and Environmental Implications of Shared Autonomous Vehicles, Using Agent-Based Model Scenarios," *Transportation Research Part C: Emerging Technologies*, Vol. 40, pages 1-13, March 2014.
Citation at http://trid.trb.org/view/1304706
From the abstract: This work describes the design of an agent-based model for shared autonomous vehicle (SAV) operations, the results of many case-study applications using this model, and the estimated environmental benefits of such settings, versus conventional vehicle ownership and use. The model operates by generating trips throughout a grid-based urban area, with each trip assigned an origin, destination and departure time, to mimic realistic travel profiles. A preliminary model run estimates the SAV fleet size required to reasonably service all trips, also using a variety of vehicle relocation strategies that seek to minimize future traveler wait times. Next, the model is run over one-hundred days, with driverless vehicles ferrying travelers from one destination to the next. During each 5-min interval, some unused SAVs relocate, attempting to shorten wait times for next-period travelers. Case studies vary trip generation rates, trip distribution patterns, network congestion levels, service area size, vehicle relocation strategies, and fleet size. Preliminary results indicate that each SAV can replace

around eleven conventional vehicles, but adds up to 10% more travel distance than comparable non-SAV trips, resulting in overall beneficial emissions impacts, once fleet-efficiency changes and embodied versus in-use emissions are assessed.

Evaluation

Performance Measurement Evaluation Framework and Co-Benefit/Tradeoff Analysis for Connected and Automated Vehicles (CAV) Applications: A Survey, Danyang Tian, Guoyuan Wu, Kanok Boriboonsomsin and Matthew J. Barth, National Center for Sustainable Transportation, September 2017.
https://ncst.ucdavis.edu/wp-content/uploads/2017/09/NCST_Qi-UCR_Perf-Measurement-Eval-Framework-and-Co-Benefits-Tradeoff-Analysis-for-CAV-Apps_Final-Report_SEPT-2017.pdf
From the abstract: This paper first proposes a broad classification of CAV applications, i.e., vehicle-centric, infrastructure-centric, and traveler-centric. Based on a comprehensive literature review, a number of typical CAV applications have been examined in great detail, where a categorized analysis in terms of MOEs [measures of effectiveness] is performed. Finally, several conclusions are drawn, including the identification of influential factors on system performance, and suggested approaches for obtaining co-benefits across different types of MOEs.

Benefits Estimation Framework for Automated Vehicle Operations, Scott Smith, Jeffrey Bellone, Stephen Bransfield, Amy Ingles, George Noel, Erin Reed and Mikio Yanagisawa, Intelligent Transportation Systems Joint Program Office, August 2015.
https://ntl.bts.gov/lib/55000/55400/55443/AVBenefitFrameworkFinalReport082615_Cover1.pdf
From the abstract: This report presents a framework for estimating the potential benefits and dis-benefits of technologies contributing to the automation of the Nation's surface transportation system. Components of the framework include (1) Safety: exposure to near-crash situations, crash prevention, and crash severity reduction; (2) Vehicle mobility: vehicle throughput, both in car following situations and at intersections; (3) Energy/environment: fuel consumption and tailpipe emissions; (4) Accessibility: personal mobility, for motorists and nonmotorists; (5) Transportation system usage: response of travelers to changes in mobility and accessibility, as well as potential new modes of transportation such as increased car sharing; (6) Land use: effects of automation on land use, and (7) Economic analysis: the macro-economic impacts of all of the above changes.