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Assessing the regional energy impact of connected vehicle deployment

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Abstract

Connected and automated vehicle technologies are likely to have significant impacts on not only how vehicles operate within the transportation system, but also on how individuals behave and utilize their vehicles. While many connected and autonomous vehicle technologies have the potential to increase network throughput and/or efficiency, i.e. connected adaptive cruise control, eco-signals, many of these same technologies have a secondary effect of reducing driver burden which can drive changes in travel behaviour. Such changes in travel behaviour, in effect lowering the cost of driving, have the potential to greatly increase the utilization of the transportation systems with concurrent negative externalities such as congestion, energy use, emissions, and so on, working against the positive effects on the transportation system due to increased capacity. To date relatively few studies have analysed the potential impacts on CAV technologies from a systems perspective, often focusing on gains and losses to an individual vehicle, at a single intersection, or along a corridor. However, travel demand and traffic flow is a complex, adaptive, non-linear system, so in this study we use an advanced transportation systems simulation model, POLARIS, which includes co-simulation of travel behaviour and traffic flow, to study potential impacts of several connected and automated vehicle technologies at the regional-level. We have analysed potential impacts, in terms of changes in vehicle miles travelled, over various market penetration levels for a feasible range of changes in travel time sensitivity to determine a potential range of VMT impacts from CAV.

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Keywords: Activity-based modeling, energy use, connected and autonomous vehicles

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1. Introduction

Automated vehicle technologies might have significant impacts on many aspects of the transportation system. Various CAV technologies, such as connected adaptive cruise control, assisted driving or autopilot systems, or connected intersections among others, will change not only how vehicles operate within the transportation system, but also on how individuals behave and utilize their vehicles. Much of the focus to date has been on how individual technologies may increase network throughput and/or efficiency, enhance safety, and offer other positive benefits to the overall transportation system. However, many of these same technologies have a secondary effect of reducing driver burden which can drive changes in travel behaviour. Such changes in travel behaviour, in effect lowering the cost of driving, have the potential to greatly increase the utilization of the transportation systems with concurrent negative externalities such as congestion, energy use, emissions, and so on, working against the positive effects on the transportation system due to increased capacity and efficiency. Therefore, understanding the impacts of CAV technologies on the demand for travel, becomes an important component to quantifying the overall impact of such technologies. To date relatively few studies have analysed the potential impacts on CAV technologies from a systems perspective, often focusing on gains and losses to an individual vehicle, at a single intersection, or along a corridor.

In this study we use an advanced transportation systems simulation model, POLARIS, which includes co-simulation of travel behaviour and traffic flow, to study potential impacts of several connected and automated vehicle technologies at the regional-level. We have analysed potential impacts, in terms of changes in vehicle miles travelled, over various market penetration levels for a feasible range of changes in travel time sensitivity to determine a potential range of VMT impacts from CAV. In order to demonstrate regional energy use impacts from potential CAV deployment, we have used POLARIS to develop a travel demand model for Ann Arbor, Michigan. The model consists of an activity-based demand model implemented as a series of actions and behaviors that the traveler agents perform during the simulation, and a network model that includes individualized routing and traffic simulation based on the kinematic wave theory of traffic flow. The model represents a complete integration of the activity-based and network simulation elements as behaviors of a single, persistent traveler agent. The models in the system are updated with local travel survey and data derived from vehicle traces from the connected vehicle safety pilot. Finally, the model is connected to the Autonomie vehicle simulation model through simulated trajectories to assess energy impacts of various connected vehicle technologies which are incorporated in the model.

2. Literature review

Possible changes in travel demand due to connectivity (V2V and V2I) and increased automation are uncertain, and estimates from the few studies of travel demand impact vary widely, especially for high levels of automation. Fagnant and Kockelman (2015) and Brown et al (2013) reviewed several such sources, and list possible ways that vehicle automation may impact travel behavior including: providing mobility for non-drivers, changes in parking patterns due to self-parking cars, increased travel by underserved population segments (e.g, young children and disabled), and increased travel induced by a lower perceived cost of travel time.

In addition, if crashes and congestion are reduced, travel may be faster and more reliable, and travel demand may increase. Less congestion and fewer crash delays would effectively increase capacity, which could induce increased travel. Travel demand induced by increased capacity was reviewed by Cervero (2001) who reported a range of elasticities of urban VMT with respect to lane-miles of 0.47 to 1.0. However, capacity increases from vehicle connectivity and automation are not the same as an increase in lane-miles; they may increase throughput on existing lanes, but do not increase network connectivity or accessibility to more destinations. Hymel et al (2010) estimated elasticities of VMT with respect to lane-mi, disaggregating the VMT change due to a change in road-miles from that due to a change in lane-miles (at constant road-miles), and found much lower values for the elasticity with response to lane-miles: 0.037 short-run, 0.186 long-run. This indicates that increasing capacity by vehicle connectivity and automation without increasing network connectivity with new roads would induce less VMT increase than the elasticities reported by Cervero would imply, however, the influence of CAVs on future VMT is highly uncertain, and depending on how CAVs will be adopted and used.

In a recent report, KPMG projected personal travel in the U.S. to increase by approximately 500 million person-miles-traveled (PMT) due mostly to population growth, but PMT could increase by twice this amount due to increased use of mobility-as-a service, enabled by connectivity and automation, especially by persons 16-24 years old and 65-84 years old. Corresponding increases in VMT are highly uncertain due to the uncertainty in average vehicle occupancy, depending on the adoption of ridesharing and automated vehicles which may travel unoccupied part of the time.

A wide range of potential VMT impacts was estimated by MacKenzie et al (2014): VMT increase of 4-13% with partial vehicle automation (e.g., driver assist), and 30-160% for full automation. A large component of the VMT impact was the change in the value of travel time. They assumed a range of travel time value in fully automated vehicles from 20% to 50% of the value of time spent driving a conventional vehicle.

Childress et al (2015) assessed the potential change in patterns in the Puget Sound region in scenarios modeled using an activity-based travel model. Scenarios analyzed included a 30% increase in existing roadway capacity, which resulted in a 3.6% increase in VMT, a decrease in perceived value of travel time cost of 35% for the highest-income households in addition to the 30% increase in capacity, which gave a VMT increase of 5.0%. In a third scenario, which assumed that everyone owned an automated vehicle (none of which were shared), a 30% increase in roadway capacity, and a 50% reduction in parking costs, VMT increased 19.6%, with an increase in average commuting distance of 60%. Notably in the third scenario Childress et al found increased delays (17.3% increase in vehicle-hours-traveled). They remarked that people may be more willing to travel in congested conditions in automated vehicles.

Gucwa (2014) used another activity-based model to simulate travel in the San Francisco Bay area under different assumptions about the resulting capacity increases from automation (none, 10% and doubling). He estimated a 4 to 8% increase in VMT (up to 14.5% increase if a zero cost of travel time was assumed for traveling in an automated vehicle). Neither Gucwa nor Childress et al. model changes in land use, e.g., changes in spatial distributions of residences or job locations. With such changes included, VMT increases could be significantly higher.

The potential increase in travel by the underserved is also very uncertain. Harper et al (2015) examined travel by people with medical conditions, non-drivers, and the elderly in the 2009 National Household Travel Survey (NHTS), and they estimated a total potential increase of VMT of 12%. Brown et al. (2014), also using NHTS data, estimated a potential increase of up to 50% in VMT by underserved, based on different assumptions about how each segment would increase their travel in automated vehicles. Using more conservative assumptions, MacKenize et al (2014) analyzed travel by young and elderly in the NHTS, and estimated possible increases of VMT from 2 to 10%. All of these estimates assumed travel by underserved would be facilitated by a fully automated vehicles, since little impact on travel by this population would be expected from partial automation.

This study, then, builds on past work by Gucwa and Childress et. al., by analyzing potential changes in travel demand due to various CAV deployment scenarios and potential behavior impacts. In this case we utilize a unique transportation systems simulation model where travel demand and traffic flow are directly and continuously integrated, to model likely scenarios. The research incorporates the analysis of demand under a feasible range of travel time valuations, and incorporates research on link capacity changes under various market penetration levels of CACC to formulate the scenarios. Next, the activity-based model which forms the basis for the research is discussed.

3. POLARIS activity-based transportation system simulation model

The POLARIS activity-based travel demand simulation model is a fully-integrated simulation of both person travel and intelligent transportation system operations that has been developed using an agent-based modeling framework (Auld et al 2015). The model consists of a series of components found in travel demand, network simulation and operations models. At the center of the model is a person-agent which represents the travelers in the system and their activity and travel planning behavior. The travellers operate in an environment represented by the transportation network agents to handle movements through the system. The various components are discussed in the following section.

3.1. Activity-based travel demand modelling

The POLARIS Integrated activity-based travel demand and transportation systems simulation model (Auld et al 2015), was used in to simulate potential changes due to CAV. POLARIS includes an activity-based demand model which is implemented as a series of actions and behaviors that traveler agents engage in during the simulation process for generating their activity-travel needs. The demand behaviors modeled include time-dependent activity generation, within simulation activity attribute planning and re-planning, and a detailed activity scheduling model which resolve schedule conflicts and maintains a consistent daily schedule for the agent. The demand components are also responsive to network and traffic management events, which can result in agent re-planning. The demand components implemented in the POLARIS demonstration model derive from previous work in modeling activity-planning and scheduling behaviors found in the development of the ADAPTS (Agent-based Dynamic Activity Planning and Travel Scheduling) model (Auld and Mohammadian 2009). The demand model is an activity-based computational process model, which simulates the underlying activity and travel planning and scheduling processes. The model continuously integrates with traffic simulation where the generation, planning and scheduling of activities occurs in continuous time and is co-simulated along with the time-dependent traffic simulation.

The planning behaviors implemented in the model include destination choice, route choice, mode choice, etc. all include cost components relating to the expected travel time which vary based on a number of factors that theoretically may change under CAV deployment by reducing the burden associated with travel. For example, the location choices and mode choices for generated activities are made using a variation of the MNL random utility maximization model, where one of the utility components is the travel time to the destination, or using the selected mode. By varying the utility parameters for travel time we can represent changes in travel time valuations for subgroups of the overall modeled population which have access to CAV technologies. It is important to note that the choices are still constrained by scheduling, resource availability, time availability and other constraints, as well as the temporal and spatial distribution of activity opportunities, available modes, etc. Next, the traffic simulation model is discussed.

3.2. Traffic simulation

The traffic simulation model involves solving a set of partial differential equations for the Newell's Simplified Kinematic Waves Traffic Flow model (Newell, 1993). The model is used as the traffic simulation model agent in the POLARIS framework. The traffic simulation model includes a set of traffic simulation agents for intersections, links, and traffic controls, which take input from the individual route choice and movement actions of the person agent. Given as input a set of travelers with route decisions and the traffic operation and control strategies in the network, the network simulation model agent simulates traffic operations and controls to provide capacities and driving rules on links and turn movements at intersections. With these capacity and driving rule constraints, link and intersection agents simulate the traffic flows using cumulative departures and arrivals as decision variables based on the Newell's Simplified model, which then determines the network performance for the route choice model, the demand model, and as well as the ITS model in the integrated framework. The traffic simulation model agents also produce a set of measures of effectiveness (MOE) such as average speed, density, and flow rate, as well as individual vehicle trajectories.

Within the traffic simulation model, traveler decision making is represented as a set of route choice and route re-planning behaviors. The route choice model describes traveler agents' dynamic route choice decisions with response to pre-trip and en-route traffic information. All travelers are assumed to be able to access prevailing traffic information prior to departure. Equipped travelers can access real-time traffic information during their trip through their equipped devices with navigation services using real-time traffic information. Unequipped travelers can access real-time traffic information disseminated from a TMC through ATIS dissemination infrastructures such as VMS and Radio to respond to both recurrent and non-recurrent traffic congestions. A bounded rationality en-route switching model (Jarakrishnan et al. 1994) is used to realistically address the en-route switching behavior of traveler agents. This route choice modeling framework also incorporates traveler agents' dynamic route choice decisions with response to experienced traffic by comparing experienced route travel time to the expected travel time as each network node is traversed (i.e. if the current route is performing poorly the bounded rationality switching model is triggered), and by implementing a look-ahead function in which the real-time travel time for the next link is evaluated. This allows traveler routes to evolve and respond to congestion even in the absence of ATIS. Route switching is also triggered through interaction with VMS or radio by comparing messages against the links in the current trip, and evaluating the travel route incorporating the message information. In the route choice model for each traveler agent, we implement a weighted A-Star shortest path algorithm. This implementation allows the parallelization of route calculations by each individual, and enables heterogeneous route cost functions to be utilized, which can incorporate the effects of CAV technology availability to individual travelers. For example, travelers with CACC may seek to minimize non-highway travel due to the perceived reduction in burden while traveling on the highway.

3.3. CACC and automation impacts on traffic flow

Cooperative adaptive cruise control (CACC) combines the adaptive cruise control with the vehicle to vehicle communication that allows improved speed control strategies. Forward vehicles communicate information about downstream traffic and provide speed recommendations. The goal of CACC is to improve three metrics associated with a transportation system, namely mobility (reduce congestion), sustainability (reduction in energy used) and safety. This improvements come from reduced headways between vehicles while maintaining traffic flow speed, and thus improving road throughput and avoiding traffic flow breakdowns at high density traffic flows. CACC improves on autonomous adaptive cruise control by allowing vehicle to receive information about lead vehicle earlier that allows to develop better control algorithms (Lu 2011) and keep the following distance as close as 0.6 seconds (Nowakowski 2010). Additional energy reduction benefits come from reduced drag forces experiences by following vehicles due to reduced air resistance. There are several studies that show energy benefits of truck and vehicle platoon in isolated test environments that utilize tightly-coupled platooning.

A study involving 3 trucks driving at distance of 0.45 seconds at the speed of 80 km/h was presented in Tsugawa 2013. The control algorithms for lateral movement relies on radar measurements as well as communication between the vehicles. Analysis of the field data shows 14% savings in energy.

Under similar speed (60 and 80 km/h) and headway conditions (from 0.3 to 0.45 seconds) a platoon of two trucks we studied by Bonnet (2000). The trucks were connected through an electronic system that consists of a vehicle to vehicle controller, a tow bar controller and image processing unit. Overall, the reduction in fuel consumption ranged from 15 to 21 percent at 80 km/h, and 10 to 17 percent at 60 km/h. There was a 3 percent fuel consumption error factor at 80 km/h, and a 4.4 percent fuel consumption error factor at 60 km/h.

Browand (2004) studied fuel consumption of two tandem trucks linked via an electronic control system and report 8-11% fuel savings. Alam (2010) tested speed control algorithms for follow vehicle that uses information about the road ahead sensed by the lead vehicle. They showed 5-8% fuel efficiency improvement. Computational fluid dynamics simulation performed by Davila (2013) confirm the field studies and show that optimal headway distance to reduce the drag forces is 6-8 meters and potentially lead to 7-15% fuel savings. Similar studies were performed for light duty vehicles (Shida 2009, 2010, Eben 2013, Shladover 2013). Fuel efficiency improvements with CACC using constant-time-gap-following criteria in normal traffic conditions have not yet been demonstrated.

Several simulation studies showed that CACC that enables shorter following gaps increases capacity from the typical 2200 vehicles per hour to almost 4000 vehicles per hour at 100 percent market penetration. We studied impact of CACC vehicles at different market penetration rates on a regional scale by adjusting the capacities of road links according to the values reported in Vander Werf (2002) and Shladover (2012). It their study Vander Werf et al (2002) estimated the effects of CACC using Monte Carlo simulation based approach that utilizes detailed models of vehicle control. Figure 1 below shows the relationship between CACC vehicle penetration level (percent of equipped vehicle presented in the traffic flow) and improvement in the road capacity.

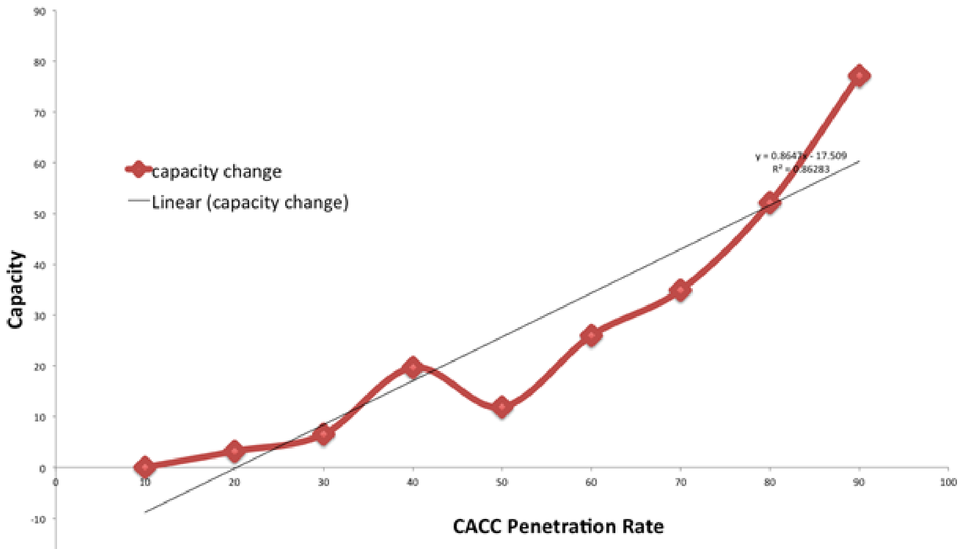

Fig. 1. Capacity change vs. market penetration of CACC

However, improvement in mobility metrics might lead to secondary impacts, such as increase in travel demand. The goal of this paper is to study the interaction between the improved traffic flow and changes in demand induced by reduced congestion.

3.4. Energy use analysis with Autonomie

Energy consumption for the regional model is predicted using the Autonomie vehicle energy use simulation system. Developed at Argonne National Laboratory, Autonomie is a modeling environment for vehicle powertrains that has a focus on energy consumption and performance. It allows the user to quickly build a powertrain model from individual configuration files, plant models, and controllers and to simulate it in a broad range of predefined processes (e.g., standard drive cycles). The models and supporting calculations are written in Simulink® and MATLAB®. Autonomie includes dozens of ready-to-run advanced powertrain models for hybrids, plug-in hybrids, electric vehicles, fuel cell vehicles, etc. Many component and vehicle models have been validated using test data from Argonne's Advance Powertrain Research Facility (APRF). Typical use cases involve running one or several vehicles on predefined deterministic drive cycles (such as the U.S. Environmental Protection Agency's urban drive cycles). The POLARIS travel demand model, however, provides an unlimited number of stochastic speed profiles for a given itinerary. By running a fleet of representative vehicles on a large number of stochastic speed profiles, we can analyze energy consumption or other operations on a broad range of trips, for evaluating the energy impact of various policies of forecast scenarios, such as future CAV deployment.

Due to the detailed, second-by-second speed profiles required for estimating vehicle energy use by Autonomie, a process was needed to convert the meso-level trajectories generated by the POLARIS network simulator into a usable format. The POLARIS simulator generates vehicle starts and stops on each link, along with average experienced travel speed, stop time at intersections and queue length at stopping. These inputs align with previous research on estimating detailed speed profiles from link-by-link profiles using NOKIA/HERE ADAS-RP data (Karbowski et al. 2014). The fundamental aspect of this approach is that vehicle speed can be modeled as a Markov chain, i.e., a random variable with the Markov property: the next state only depends on the current state, and not on the sequence of past events, and is governed by a transition probability matrix. The collection of transition probabilities is built from real-world observations obtained from Chicago Metropolitan Agency for Planning (CMAP) as part of a 2007 comprehensive travel survey for the greater Chicago area (CMAP 2008). GPS loggers were provided to a subset of the 267 surveyed households that participated in the data collection, mostly for more than week. Close to 10,000 vehicle trips were recorded, for a total of 6 million data points. The data was filtered and then used to generate the speed TPM, which was then applied to the POLARIS outputs for each case study. See Karbowski et al (2014), for more detail on the methodology.

4. Case study analysis

4.1. Ann Arbor metropolitan area model

The POLARIS model of the Ann Arbor-Ypsilanti, Michigan metropolitan area has been developed based on an existing regional travel demand from the Southestern Michigan Council of Governments, using local survey data, network information from SEMCOG and OpenStreetMap, and trip and O-D flow information derived from the Connected Vehicle Safety Pilot study. The model includes the multimodal transportation planning network covering Washtenaw County, Michigan. The transportation planning network includes 11265 links and 8,659 nodes, and is shown in Figure 2. There are approximately 290 thousand travelers living in 123 thousand households in the region, engaging in 1.2 million trips on an average day, all of which are simulated in the POLARIS model. Note, however, that only the portion of trips internal to the model are considered in the model results.

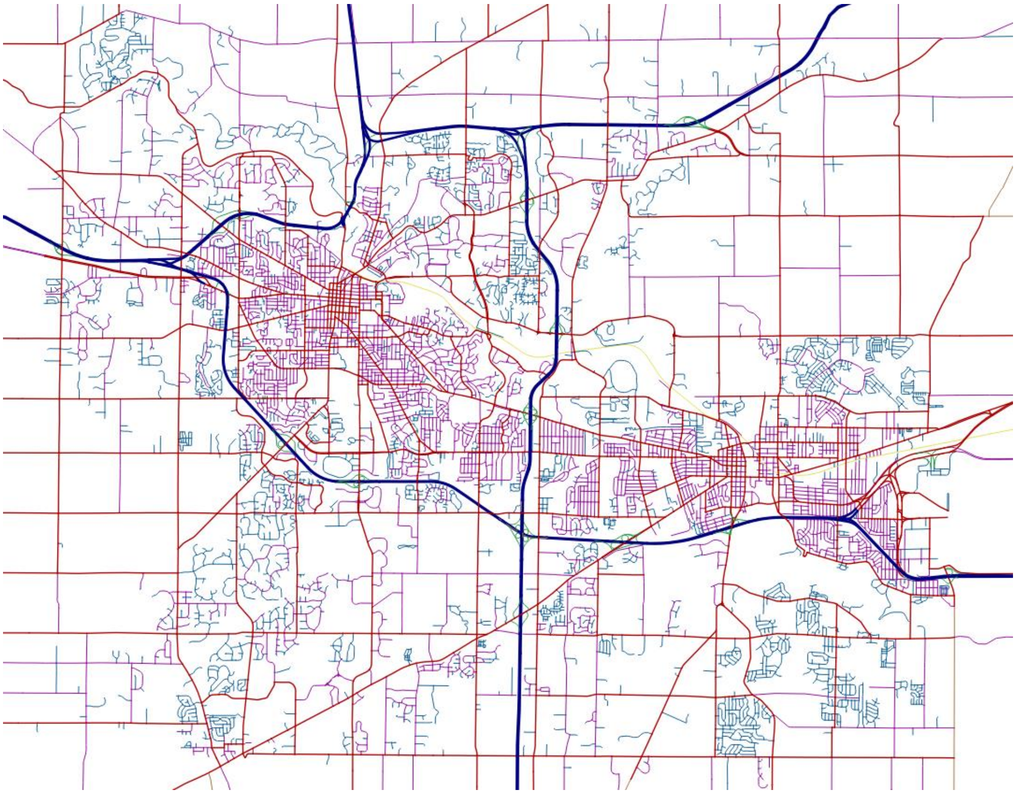

Fig. 2. Ann Arbor model transportation network

4.2. Scenario setup

The scenario definition for the CAV study involves the variation of several model variables in the baseline POLARIS travel demand model. First is the CAV technology market penetration, which determines which travellers are randomly assigned to possess CAV technology. It is important to note that the remainder of the scenario variables are only modified for travelers with CAV technology. Next, the change in traveler value of travel time savings (VOTT) is specified. This is implemented as a reduction in any travel time parameters in the underlying choice models as discussed above. Due to a lack of empirical data on VOTT changes due to CAV, the values for VOTT changes were varied from no change to 75% reduction which was found to be a feasible range in the literature, i.e. Mackenzie et al (2013). The capacity increase on individual road segments was also varied over different scenarios in two ways. In one set of scenarios, the capacity change alone was varied from 12% increase to 77% increase - representing feasible ranges from the Shladover et al study (2012). In the remaining scenarios, capacity was changed according to the previously described relation between capacity and market penetration. Finally, in scenarios where CAV technology penetration was 100%, we also assume that intersections can be automated and intersection control is turned off in the model. The input variable ranges can all be seen in Table 1.

4.3. Scenario analysis results

The baseline Ann Arbor model, and the 18 additional scenarios described in Table 1, were all simulated using POLARIS. The POLARIS model outputs changes for each individual traveler as well as changes in overall vehicle miles travelled (VMT), vehicle hours travelled (VHT) and average travel time. The comparison between the results for each scenario is shown in the table. In general, it is seen that all of the scenario changes have the effect of increasing vehicle miles travelled.

Table 1. Scenario setup and analysis results

Scenario type	Market pen.	VOTT change	Capacity increase	Auton. Inter.	VMT in MM (% change)	VHT (in 000)	avg travel time (min)
1. baseline	0%	0%	0%	no	5.33 (0.00%)	154.7 (0.0%)	12.2 (0.0%)
2. Capacity increase only	0%	0%	12%	no	5.35 (0.36%)	152.2 (-1.6%)	12.0 (-1.8%)
3. Capacity increase only	0%	0%	50%	no	5.44 (1.99%)	149.0 (-3.7%)	11.7 (-4.0%)
4. Capacity increase only	0%	0%	77%	no	5.44 (2.04%)	147.7 (-4.5%)	11.6 (-4.5%)
5. VOTT only - low pen.	20%	-25%	0%	no	5.41 (1.34%)	157.4 (1.8%)	12.4 (1.8%)
6. VOTT only - low pen.	20%	-50%	0%	no	5.49 (2.93%)	161.2 (4.2%)	12.7 (4.1%)
7. VOTT only - low pen.	20%	-75%	0%	no	5.60 (4.98%)	166.3 (7.5%)	13.0 (7.1%)
8. VOTT only - high pen.	75%	-25%	0%	no	5.64 (5.77%)	167.6 (8.4%)	13.2 (8.0%)
9. VOTT only - high pen.	75%	-50%	0%	no	5.96 (11.81%)	183.5 (18.6%)	14.4 (18.0%)
10. VOTT only - high pen.	75%	-75%	0%	no	6.33 (18.59%)	202.4 (30.9%)	15.8 (29.9%)
11. All effects - low pen	20%	-25%	3%	no	5.42 (1.61%)	157.5 (1.8%)	12.4 (1.6%)
12. All effects - low pen	20%	-50%	3%	no	5.52 (3.56%)	162.2 (4.8%)	12.7 (4.3%)
13. All effects - low pen	20%	-75%	3%	no	5.62 (5.32%)	166.3 (7.5%)	13.0 (7.1%)
14. All effects - med pen	50%	-25%	12%	no	5.56 (4.32%)	160.2 (3.5%)	12.6 (3.2%)
15. All effects - med pen	50%	-50%	12%	no	5.79 (8.59%)	170.5 (10.2%)	13.3 (9.6%)
16. All effects - med pen	50%	-75%	12%	no	6.01 (12.73%)	180.2 (16.5%)	14.1 (15.9%)
17. All effects - high pen	100%	-25%	77%	yes	5.87 (10.00%)	162.6 (5.1%)	12.7 (4.5%)
18. All effects - high pen	100%	-50%	77%	yes	6.36 (19.32%)	182.2 (17.8%)	14.2 (16.5%)
19. All effects - high pen	100%	-75%	77%	yes	6.84 (28.19%)	203.9 (31.8%)	15.8 (30.1%)

The results for capacity changes induced by CACC alone can be seen in the results by comparing scenarios 1-4. It is seen here that increase in capacity increases overall VMT, although only to a small degree, with about 2% induced additional VMT for an increase in capacity of almost 80%. The elasticity of VMT with respect to capacity of 0.027 is in line with short run estimates found in Hymel et al (2010) of 0.037, which is reasonable as this model is focused on short run, i.e. daily activity choices rather than long term choices such as residence or workplace, changes in which can induce additional demand.

Next, we look at the impact of value of travel time changes in isolation, with no change in roadway capacity due to the technology. In Figure 3, the results for the two cases, low (20%) and high (75%) market penetration, for a variety of feasible VOTT reductions are shown. The VOTT reduction values represent current conditions (0% reduction), high VOTT reduction (75%) and two points in between, similar to values used in other studies. The high VOTT reduction figure assumes travel time in CAVs is similar in comfort, convenience, etc as travel in high quality transit. Overall, we find that reducing travel time cost significantly increases VMT, with a 5% increase in VMT for the high VOTT reduction case at low penetration levels and a 19% increase at high penetration levels. As expected, reducing the cost of travel increases the consumption of travel. Similarly, there is an increase in hours spent traveling (VHT), with over 30% increase at the high penetration, low value of travel time scenario, which is as expected, given the lower disutility associated with travel time in this scenario. Interestingly, the time spent traveling increases at a greater rate than the distance traveled, indicating a substantial increase in delay caused by increasing congestion.

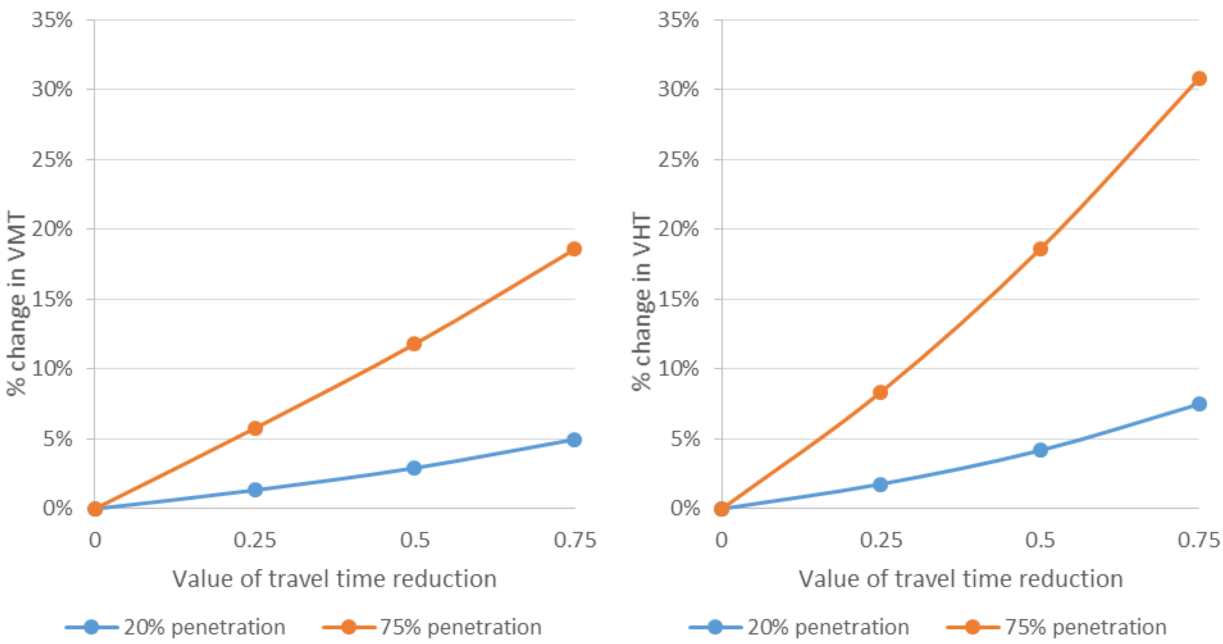

Fig. 3. (a) VMT change and (b) VHT change vs VOTT change by market penetration (no capacity change)

The results for the scenarios where all effects are evaluated simultaneously are shown in Figure 4. In this figure, the VMT and VHT changes are plotted against market penetration levels for three different VOTT reduction levels, where the capacity change is modeled based on the given market penetration according to Figure 1. In this case, we have VMT changes with 100% market penetration ranging from 10% for a 25% VOTT reduction up to 28% for a 75% VOTT reduction. The estimate of a 5% increase in VMT due to a 35% reduction in VOTT and 30% increase in capacity estimated by Childress et al (2015) appear to align with these results (assuming the 30% increase in capacity arises from ~60-70% market penetration. The same parameters would seem to result in approximately a 6-7% increase given our model results. These results demonstrate the wide uncertainty resulting from potential behavioral changes from CAV, which are still largely unknown due to low levels of deployment of such technologies.

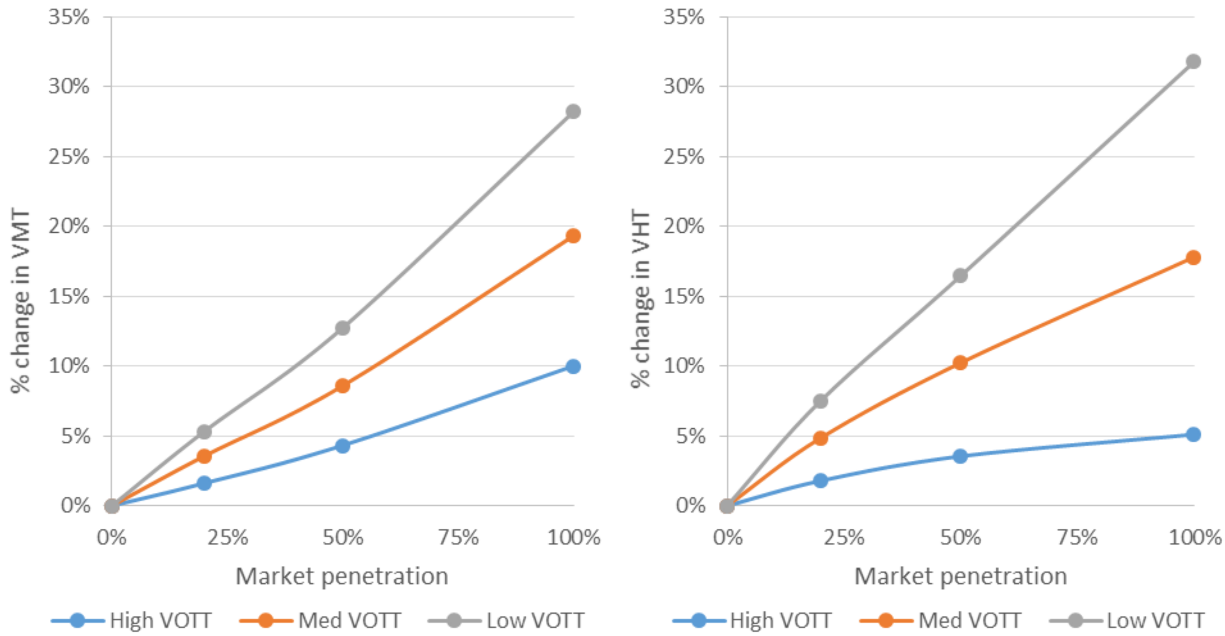

Fig. 4. (a) VMT change and (b) VHT change by market penetration and VOTT change (all effects)

Finally, for the energy analysis, we focus on comparing three scenarios: baseline, medium CAV deployment (scenario 15) and high CAV deployment (scenario 19). A random 1% sample of trajectories from each scenario run was selected and run through the speed reconstruction process described in Section 3.4. Each reconstructed trajectory (consisting of second-by-second speed measurements) was then randomly assigned to a vehicle type according to the fleet distribution shown in Table 2, which includes a representative mix of vehicle classes and powertrains. The vehicle combined with each trajectory was then run through the Autonomie simulation to generate fuel consumption, state of charge and other vehicle characteristics for each trip.

Table 2. Vehicle Type Distribution

Vehicle Class	Powertrain	Share (%)
Compact	Conventional	27.0%
Midsize	Conventional	29.0%
Small SUV	Conventional	17.0%
Midsize SUV	Conventional	9.0%
Pickup	Conventional	15.0%
Compact	HEV	2.0%
Midsize	HEV	0.5%
Small SUV	HEV	0.3%
Midsize SUV	HEV	0.1%
Pickup	HEV	0.2%

The aggregate results for each scenario can be seen in Table 3. Overall, the high CAV scenario shows a 33.7% increase in fuel consumed, with only a 6.7% increase in total trips and a 28% increase in total distance traveled, demonstrating the effect of increased congestion. The distribution of fuel consumption per trip is shown in Figure 5, where there is a clear increase in high consumption trips (> 0.5 kg) in the high-CAV scenario

Table 3. Scenario results

	Trips	% change	Fuel cons. (kg)	% change
Base	746,000	–	272,429	–
Med. CAV	764,000	2.4%	296,804	8.9%
High CAV	796,000	6.7%	364,123	33.7%

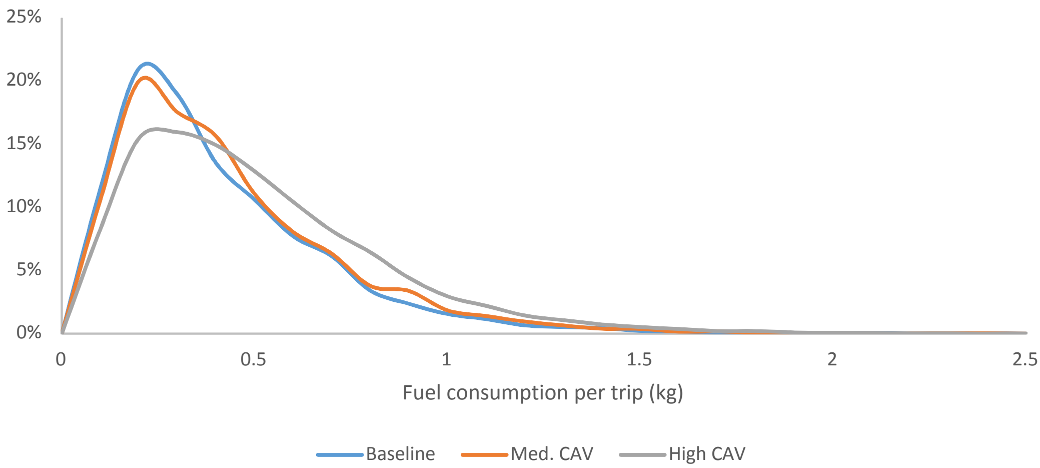

Fig. 5. Fuel consumption distribution (in kg) for each scenario

5. Discussion and conclusions

In this research, we have applied an integrated transportation system model to analyze the impact of CACC (cooperative adaptive cruise control) and other potential CAV technologies on the performance of the transportation network and changes of mobility patterns in the Ann Arbor region. The transportation system model which was used, POLARIS, allows for analysing the interconnection between the changes in the congestion levels, traveller behaviour and activity patterns, and with the connection to the Autonomie vehicle energy use simulation software, can also analyze regional energy consumption. We have looked at a wide range of potential scenarios, varying the market penetration, capacity changes and travel time valuations. Our results show that changes in capacity increase overall VMT, although only to a small degree, with about 2% induced additional VMT for an increase in capacity of 77%. The elasticity of VMT with respect to capacity of 0.027, which is in line with previous research. In contrast, changes in travel time cost, or value of travel time savings, have a significant impact, especially at very low levels of VOTT, increasing VMT by up to 28%. Along with the 28% increase in VMT there is a 33% increase in energy usage, indicating substantial secondary effects and increasing congestion, even when capacity is significantly increase. This analysis provides potential feasible bounds for impacts of CACC and other CAV technologies over a range of penetration levels, but much uncertainty still exists.

There are several possible improvements to the methodology used for analysis. An assumption on uniform spatial distribution of the CACC equipped vehicles in the region can be improved by using a probabilistic model that relates the socio-demographic characteristics of people to the likelihood of owning a vehicle. Such models exist for other vehicle technologies, such as electric vehicles and can be potentially be used to improve the assumptions about the automated vehicles. Further, the changes in capacity was uniformly applied to every road segment on the network and was simply equal to the CACC technology penetration rate in the region. Improved traffic flow model would allow to dynamically adjust each of the road segments capacity given the number of CACC vehicles present on that specific link.

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References

Alam, Assad A., Ather Gattami, and Karl Henrik Johansson. "An experimental study on the fuel reduction potential of heavy duty vehicle platooning." Intelligent Transportation Systems (ITSC), 2010 13th International IEEE Conference on. IEEE, 2010.

Auld, J.A. and A. Mohammadian (2009). Framework for the Development of the Agent-based Dynamic Activity Planning and Travel Scheduling (ADAPTS) Model. Transportation Letters, International Journal of Transportation Research, 1 (3), 245-255.

Auld, J.A., M. Hope, H. Ley, V. Sokolov, B. Xu and K. Zhang (In press). POLARIS: Agent-Based Modeling Framework Development and Implementation for Integrated Travel Demand and Network and Operations Simulations. Transportation Research Part C: Emerging Technologies.

Bonnet, C., & Fritz, H. (2000). Fuel consumption reduction in a platoon: Experimental results with two electronically coupled trucks at close spacing (No. 2000-01-3056). SAE Technical Paper.

Browand, F., McArthur, J., & Radovich, C. (2004). Fuel saving achieved in the field test of two tandem trucks. California Partners for Advanced Transit and Highways (PATH).

Brown, A.; Gonder, J.; Repac, B. (2014). “An Analysis of Possible Energy Impacts of Automated Vehicles.” Springer Book Chapter

Childress, S., Council, P. S. R., Nichols, B., Charlton, B., & Coe, S. (2014). Using an Activity-Based Model to Explore Possible Impacts of Automated Vehicles, 94th Annual Transportation Research Board Meeting, paper 15-5118.

Dávila, A. (2013). SARTRE Report on Fuel Consumption. Technical Report for European Commission under the Framework 7 Programme Project 233683 Deliverable 4.3). Cambridge, UK: Ricardo UK Limited. Available: http://www. sartreproject. eu/en/publications/Documents/SARTRE_4_003_PU. pdf.

Eben Li, S., Li, K., & Wang, J. (2013). Economy-oriented vehicle adaptive cruise control with coordinating multiple objectives function. Vehicle System Dynamics, 51(1), 1-17.

Fagnant, Daniel J. and K. Kockelman. “Preparing a Nation for Autonomous Vehicles: Opportunities, Barriers and Policy Recommendations,” Transportation Research Part A: Policy and Practice, 77 (July 2015): 167-181.

Freeway Traffic Flow. Transportation Research Record No. 2324, pp. 63-70, 2012

Gucwa, Michael, (2014) "Mobility and Energy Impacts of Automated Cars," Presentation to the Automated Vehicles Symposium. Burlingame, CA, July 16.

Harper, C., Mangones, S., Hendrickson, C. T., & Samaras, C. (2015). “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,” 94th Annual Transportation Research Board Meeting, paper 15-1609.

Jayakrishnan, R., Mahmassani, H. S., Hu, T.-Y., (1994). An Evaluation Tool for Advanced Traffic Information and Management Systems in Urban Networks. Transportation Research Part C, 2(3), pp. 129-147.

KPMG (2015) “The Clockspeed Dilemma: What does it mean for automotive innovation?”, November,https://home.kpmg.com/xx/en/home/insights/2015/12/the-clockspeed-dilemma-gary-silberg-head-of-automotive-kpmg-us.html

Lu, Xiao-Yun, and Steven E. Shladover. "Automated Truck Platoon Control." (2011).

MacKenzie, D., A. Wadud, P. Leiby (2013) "A First Order Estimate of the Energy Impacts of Automated Vehicles in the United States," Poster presented at Workshop on Road Vehicle Automation, Stanford Univ. Palo Alto, CA.

Newell, G. F. 1993. A simplified theory of kinematic waves in highway traffic, Part I: general theory; Part II: queueing at freeway bottlenecks; Part III: multi-destination flows. Transportation Research Part B, 27(4), 281-314.

Nowakowski, Christopher, Jessica O'Connell, Steven E. Shladover, and Delphine Cody. "Cooperative adaptive cruise control: Driver acceptance of following gap settings less than one second." In Proceedings of the Human Factors and Ergonomics Society Annual Meeting, vol. 54, no. 24, pp. 2033-2037. SAGE Publications, 2010.

Shida, M., & Nemoto, Y. (2009). Development of a Small-Distance Vehicle Platooning System. In 16th ITS World Congress and Exhibition on Intelligent Transport Systems and Services.

Shida, M., Doi, T., Nemoto, Y., & Tadakuma, K. (2010). A short-distance vehicle platooning system 2nd report–evaluation of fuel savings by the developed cooperative control. In Proc. of.

Shladover, S. E., Nowakowski, C., Lu, X. Y., & Hoogendoorn, R. (2014). Using Cooperative Adaptive Cruise Control (CACC) to Form High-Performance Vehicle Streams.

Shladover, S.E., Su, D., and Lu, X.-Y. Impacts of Cooperative Adaptive Cruise Control on

Shladover, Steven E., et al. "Cooperative Adaptive Cruise Control: Definitions and Operating Concepts." Transportation Research Board 94th Annual Meeting. No. 15-3265. 2015.

Tsugawa, S. (2013, September). An overview on an automated truck platoon within the energy ITS project. In Advances in Automotive Control (Vol. 7, No. 1, pp. 41-46).

Tsugawa, Sadayuki, Shin Kato, and Keiji Aoki. "An automated truck platoon for energy saving." Intelligent Robots and Systems (IROS), 2011 IEEE/RSJ International Conference on. IEEE, 2011.

Tsugawa, Sadayuki. "An overview on an automated truck platoon within the energy ITS project." Advances in Automotive Control. Vol. 7. No. 1. 2013.

Vander Werf, Joel, et al. "Effects of adaptive cruise control systems on highway traffic flow capacity." Transportation Research Record: Journal of the Transportation Research Board 1800 (2002): 78-84.