A FIRST ORDER ESTIMATE OF ENERGY IMPACTS OF AUTOMATED VEHICLES IN THE UNITED STATES

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Abstract

A novel comprehensive calculation bounds the long-term energy implications of road vehicle automation. We combine multiple engineering estimates of the energy-efficiency benefits of vehicle automation resulting from traffic flow improvements, intelligent speed adaptation, vehicle drag reduction through platooning, and possible vehicle size and weight variations. Many of these advantages can be brought about through relatively low level of automation and are also applicable for highly automated vehicles, such as self-driving Level 4 vehicles. However, highly-automated vehicles can have significant behavioural implications that can increase fuel consumption due to road travel. Higher speeds could offset fuel efficiency gains. Potentially lower per-mile energy costs and vehicle insurance costs (due to fewer accidents), plus a possible sharp reduction in the large cost component associated with the drivers time, can reduce total travel costs per mile. Self-driving vehicles are also hoped to enhance mobility, enabling new demographic groups travel on personal vehicles. Higher speed enabled by highly automated vehicles can also make road travel competitive with aviation (for passenger) and rail (for freight). All of these factors could increase road travel and increase energy consumption. We estimate the potential energy benefits and rebound effects using an ASIF or Kaya framework, where travel activity is endogenously determined from an economic response to estimated shifts in travel cost components, and energy intensity appears both as separate multiplicative factor and a variable contributing to the cost-based determination of activity. A wide range of potential energy outcomes highlight potentially urgent policy issues, and identify key areas for further research.
1 Background

Vehicle automation has received increasing attention of late, much of it emphasizing the potential to improve safety and traffic flow. However, automation also has the potential to radically alter transportation energy consumption patterns. The net effect of automation on transportation energy consumption and emissions is highly uncertain, depending strongly upon which potential effects of automation are realized and the degree to which automation changes travel patterns.

There is a need to get a sense of how automation may affect energy use, by how much, and to identify opportunities to support and guide an environmentally beneficial transition toward automation. This paper reviews key mechanisms through which automation may affect transportation energy consumption, quantitatively estimates the potential magnitudes of these effects, and begins to identify key leverage points at which vehicle automation can be directed toward the goal of reducing energy consumption. This is early but important exploratory work. In this paper we focus on vehicle automation as defined below, but do not encompass the full range of intelligent transportations systems (ITS), many of which can improve traffic routing and flow even without automation.

Google and Ford have predicted that self-driving cars will be on the road in 2017, and KPMG is heralding automated vehicles as “the next revolution.” Attempting to get ahead of the curve, officials in Nevada and California have scrambled to establish a regulatory framework for automated vehicles on their states’ roads. The National Highway Traffic Safety Administration has developed a policy on vehicle automation, including a taxonomy of “levels of automation” based on balance of driving control between driver and vehicle (NHTSA, 2013). This taxonomy is useful when considering the energy implications of automation:

0. Level 0 - no automation
1. Level 1 - one or more functions are automated (e.g. adaptive cruise control) but operate independently of one another
2. Level 2 - multiple automated system operate in concert (e.g. adaptive cruise control and lane-keeping systems), but driver must pay attention to roadway and be prepared to take over control immediately
3. Level 3 - limited self-driving - vehicle is fully automated under certain traffic or environmental conditions (e.g. highway driving) and driver can disengage from driving, but must be available "for occasional control, but with sufficiently comfortable transition time."
4. Level 4 - full automation - vehicle navigates entire trip from origin to destination with no involvement from the driver. Includes occupied and unoccupied vehicles.

Automated vehicles have potential to significantly change the way people travel. They may enable the adoption of energy-saving driving practices, and facilitate changes in the design of individual vehicles or the transportation system as a whole that enable reductions in energy intensity. However, in the longer run they may also significantly change the in-vehicle experience and the cost of driver time (perceived cost by private drivers or actual cost for commercial drivers) in the vehicle, which could lead to more demand for travel. The overall energy and environmental implications of automation are highly uncertain, and will depend upon:

- The degree to which energy-saving algorithms and design changes are implemented in practice;
- The degree to which automation actually leads to system-wide changes that facilitate energy savings, e.g. shared vehicles, adoption of alternative propulsion technologies and fuels;
• The degree to which reduced driver burden (and reduced cost of time spent in the vehicle) lead private travelers to spend more time and travel greater distances in their vehicles, or lead to greater commercial roadway activity.

2 Methodology
A Kaya Identity / “ASIF” accounting framework was used to model the multiple combined effects of vehicle automation on energy consumption and emissions (Schipper, 2002). The formulation is summarized in the following equation:

\[ \text{Emissions} = \text{Activity Level} \cdot \text{Modal Share} \cdot \text{Energy Intensity} \cdot \text{Fuel Carbon Content} \] (1)

\[ \text{tonnes} = \text{miles} \cdot \frac{\text{vehicle miles}}{\text{miles}} \cdot \frac{\text{BTU}}{\text{vehicle mile}} \cdot \frac{\text{tonnes}}{\text{BTU}} \] (2)

The Kaya framework provides a simple organizing structure, which permits convenient modeling of linear or log-linear effects on travel demand, mode choice, energy intensity of travel, or carbon intensity of the energy supply. The impacts of various independent effects on travel demand and energy intensity can be readily multiplied together to estimate the overall impact on energy consumption or emissions. The Kaya framework is less amenable to modeling non-independent effects, higher-order interactions and equilibrium feedbacks. For example, more travel will increase congestion, which will take back some of the increased travel demand, but also lead to increased energy intensity. These nuances are lost with the simple Kaya formulation, but it nevertheless remains useful for aggregating the main effects of automation.

Kaya multipliers were estimated for each of the key pathways by which automation may affect transportation energy consumption, which are summarized briefly in Table 1. These mechanisms were identified via a review of relevant research literature, popular press articles and online materials, and conversations with subject area experts. However, we have not included traditional ITS measures such as traveler information, efficient routing etc. since they can work as standalone systems without automation. A survey of the literature turned up data and modeling results that were used to develop the ranges for the Kaya multipliers. Where suitable results could not be found in the literature, estimates of the effects were developed using basic engineering and economic analysis, travel survey data and reasonable assumptions. These estimates are described in Sections 3, 4 and 5.

Finally, several scenarios were developed to explore the potential range of overall impacts that automation may have on energy consumption and emissions over the long term. The scenarios are not meant to be predictions, but plausible alternative visions of how the transportation system may evolve in the presence of automation. The scenarios underscore the substantial uncertainty and huge range of potential impacts that an unmanaged transition to automation could produce.
Table 1. Potential pathways to energy impacts of automated vehicles

<table>
<thead>
<tr>
<th>Pathways</th>
<th>ASIF/Kaya element</th>
<th>Vehicle or Network effect</th>
<th>Direction of effect</th>
<th>Automation level</th>
<th>Penetration level</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Congestion mitigation</td>
<td>I</td>
<td>N</td>
<td>-</td>
<td>1-4</td>
<td>Low to high</td>
<td></td>
</tr>
<tr>
<td>Eco-driving</td>
<td>I</td>
<td>V+N</td>
<td>-</td>
<td>1-4</td>
<td>Any</td>
<td></td>
</tr>
<tr>
<td>Platooning</td>
<td>I</td>
<td>V+N</td>
<td>-</td>
<td>2-4</td>
<td>Any</td>
<td>Platoons affect road capacity</td>
</tr>
<tr>
<td>De-emphasized performance</td>
<td>I</td>
<td>V</td>
<td>-</td>
<td>3, 4</td>
<td>Any</td>
<td></td>
</tr>
<tr>
<td>Improved crash avoidance</td>
<td>I</td>
<td>V</td>
<td>-</td>
<td>2-4</td>
<td>Very high, near 100%</td>
<td>Safety allows size-weight reductions</td>
</tr>
<tr>
<td>Higher highway speeds</td>
<td>I</td>
<td>+</td>
<td>-</td>
<td>1-4</td>
<td>Moderate to high</td>
<td>Step change for levels 3-4</td>
</tr>
<tr>
<td>Vehicle right-sizing</td>
<td>I</td>
<td>V+N</td>
<td>-</td>
<td>3, 4</td>
<td>High to very high</td>
<td>Smaller size affects congestion</td>
</tr>
<tr>
<td>Demand due to generalized cost reduction</td>
<td>A, S</td>
<td>+</td>
<td>-</td>
<td>1-4</td>
<td>Any</td>
<td>Step change for levels 3-4</td>
</tr>
<tr>
<td>Demand from New user groups</td>
<td>A, S</td>
<td>-</td>
<td>-</td>
<td>3, 4</td>
<td>Any</td>
<td></td>
</tr>
<tr>
<td>Car-sharing</td>
<td>A, S</td>
<td>-</td>
<td>-</td>
<td>3, 4</td>
<td>Any</td>
<td></td>
</tr>
<tr>
<td>Potential for low carbon transition</td>
<td>F</td>
<td>V+N</td>
<td>-</td>
<td>3, 4</td>
<td>Low to high</td>
<td>Automated refueling/charging</td>
</tr>
</tbody>
</table>

3 Energy Intensity Effects

Vehicle automation could potentially reduce the energy intensity of vehicle travel, by enabling more efficient operations, facilitating a shift away from the owner-driver model of personal mobility, and altering the size, weight, and efficiency of vehicles. In the sections that follow, estimates of these effects are developed based on simple analyses and reviews of the relevant literature.

3.1 Congestion mitigation

Vehicle automation may reduce the energy wasted by congestion, by improving traffic flow and reducing accident frequency (a major source of congestion). Schrank, Eisele, and Lomax (2012) have estimated the annual volume of fuel wasted due to congestion. Dividing their estimates by total on-highway gasoline and diesel consumption (from the Energy Information Administration) indicates that the fuel wasted on congestion rose steadily from 0.5% 1984 to 1.8% in 2005, and is expected to reach 2.6% by 2020. Extrapolating this trend suggests that 4.2% of fuel would be wasted due to congestion in 2050. So, the complete elimination of congestion might decrease the energy intensity of vehicle travel (light-duty and heavy-duty combined) by about 2% today and a little over 4% in 2050.

3.2 Eco-driving

Automation may facilitate the broad implementation of so-called “eco-driving,” a set of practices that tend to decrease in-use fuel consumption without changing vehicle design. Previous research suggests that optimizing the speed-acceleration profile could reduce energy intensity by up to 50% under some conditions, but only 10-15% under other conditions (He et al., 2012; Mensing, Trigui, and Bideaux, 2011, 2012; Mensing et al., 2013). Providing real-time guidance to drivers can save 10-20% (Barth and Borrioonsomsin, 2009), but drivers in simulator studies achieved widely varying results (Wu, Zhou, and Ou, 2011). Berry (2010) reviewed many eco-driving studies and found savings averaging...
20% in the short run, but closer to 10% in the long run. This decay, confirmed by Degraeuwe and Beusen (2013), points to a key advantage of vehicle automation: computers can be programmed to drive efficiently, and will not relapse into old habits the way that human drivers do.

3.3 Platooning

Platooning refers to the practice of multiple vehicles following one another closely, leading to reductions in aerodynamic drag for all of the vehicles, but particularly for the vehicles in the middle of the pack. Platooning in tight formations is unsafe without automation, because of the delays in human drivers perceiving and reacting to speed changes of the vehicles ahead.

Drag reductions from platooning depend on the shapes of the vehicles in the platoon, their ordering, and their following distances. Since savings are bigger for vehicles in the middle of the pack, average savings increase with the number of vehicles in the platoon. For two sedans, the average reduction in drag has been estimated to be 10% (Zhu and Yang, 2011). For platoons containing mixed vehicle types, drag reductions between 20% and 60% have been reported (Schito and Braghin, 2012; Duan et al., 2007). For a long platoon of vans (five or more vehicles) with short following distances, average drag reductions between 45% and 55% have been reported (Schito and Braghin, 2012), while reductions of up to 60% have been reported for the vans in the middle of a platoon with short following distances (less than half a vehicle length) (Zabat et al., 1995).

To estimate the effect of platooning on energy intensity, it is essential to consider the fraction of energy use that goes to overcoming aerodynamic drag, and the fraction of miles in which platooning could deliver a benefit. Since aerodynamic losses increase with speed, and because it is more practical to keep cars in formation at constant speeds, platooning offers significant potential for energy savings mainly in highway driving. Based on FHWA travel statistics, highway travel comprises between 33% (counting only interstates and expressways) and 55% (also including principal arterial roads) of all miles traveled in the U.S. Kasseris (2006) shows that on the U.S. Highway Fuel Economy Test cycle, about 50% of tractive energy goes to overcoming drag, and that for steady-speed travel at more typical highway speeds (90-120 km/h), drag accounts for about three-fourths of tractive energy requirements. Combining the above factors suggests that if platooning were universally adopted during highway travel for light-duty vehicles, it might reduce energy intensity by anywhere from about 3% (20% drag reduction * 50% of load * 33% of miles) up to 25% (60% drag reduction * 75% of load * 55% of miles).

For freight trucks, Tsugawa (2013) has reported a 10% reduction in energy consumption for a 3-truck platoon at 80 km/h, with a 20m gap between trucks (15% reduction at 5 m gap). Extrapolating his results toward zero gap implies a 25% reduction for the middle truck. This represents a plausible upper bound for the middle vehicles in a long platoon. Lu and Shladover (2013) reported savings of 4%, 10%, and 14% in fuel use for first, second, and third trucks, respectively, in a 3-truck platoon with 6 m spacing. Since the large majority of freight miles are on the highway, we can use these energy savings estimates directly and estimate an upper range of 10-25% energy intensity reduction from platooning of heavy trucks.

3.4 Changing highway speeds

Automation may lead to increases in highway travel speeds, if human attention and reaction times are no longer limiting factors in determining safe speeds. Since aerodynamic losses increase with speed, this could increase the energy intensity of vehicle travel.
To bound this effect, it is necessary to predict how much faster people might travel in the absence of speed limits. Currently, speed limits on most U.S. interstates and other limited-access highways range from 55-70 mph, and actual interstate speeds average 65-70 mph (White, 2010). To estimate speed in the absence of speed limits, we assume that drivers will increase their speed until the marginal value of time saved just matches the marginal cost of increased fuel consumption. Assuming a value of travel time of $18 per hour and a fuel price of $3.50 per gallon ($0.92 per liter), and assuming weight, drag, and other characteristics of a typical midsize car, suggest that light-duty vehicle speeds might increase to between 75 and 100 mph (120-160 km/h) on U.S. highways in the absence of speed limits and safety considerations, increasing energy intensity by 11-45% on the highway. This is generally consistent speeds on Germany’s Autobahn system, which average approximately 140 km/h (88 mph) on sections without speed limits (Scholz, Schmallowsky, and Wauer, 2007). These faster speeds are applied to between 33% and 55% of all distance traveled (i.e. all highway travel using FHWA metrics), yielding average energy intensity increases of 4-25% for light-duty vehicles.

On interstate highways, freight trucks currently average between 50 and 60 mph. Similar calculations as above, assuming cost of $25 for the driver’s time, show an optimum travel speed of 52 mph for a large (class 8) truck. This suggests that truck travel speeds would not necessarily be expected to increase even if speed limits were increased, particularly if advanced automation decreased the hourly cost of drivers’ time.

3.5 De-emphasized performance

Today’s new cars and trucks can accelerate from 0-97 km/h (0-60 mph) about twice as quickly as new vehicles in the early 1980s (MacKenzie and Heywood, 2012). Taking drivers “out of the loop” may reduce the demand for acceleration capabilities in light-duty vehicles, since hard acceleration may become more a source of discomfort than of visceral satisfaction.

If historic trends continued, the average acceleration of new vehicles would fall from about 8.8 seconds currently, approaching 7.8 seconds (MacKenzie & Heywood 2012). MacKenzie (2013) has estimated that (holding other vehicle attributes constant) a 1% increase in the 0-97 km/h acceleration time decreases per-kilometer fuel consumption, by 0.44%. If instead of continuing historic trends, acceleration capabilities stabilized at current levels, future energy intensity could be reduced by about 5%. If acceleration capabilities reverted to 1982 levels, fuel consumption could be reduced by 23%.

3.6 Improved crash avoidance

Since over 90% of accidents are commonly attributed to human error, automation could dramatically lower crash rates, and render crashworthiness much less important. In this situation, vehicles could become smaller and potentially shed safety equipment. These effects are highly speculative and seem unlikely to materialize until traffic risks are radically and convincingly reduced.

MacKenzie, Zoepf, and Heywood (2013) have estimated that safety features contributed 112 kg out of 1452 kg (7.7%) of the average new U.S. car’s weight in 2011. Based on common estimates of the relationship between weight and fuel consumption, such as those documented in MacKenzie (2013), removing this safety weight would decrease fuel consumption by 5.5%.

A more extreme reaction to improved crash avoidance might be consumers shifting into smaller vehicle classes, which they might deem insufficiently safe today. In 2010-2012, average fuel economy of new light-duty vehicles in the U.S. was 28.8 miles per gallon (mpg), while that of compact cars

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was 35.3 mpg (EPA, 2013). If improved crash avoidance could make everyone willing to switch to a
compact car, it could reduce average per-mile fuel consumption by about 18%. Combined with the
reduction of safety equipment, this could yield an estimated maximum 23% reduction in fuel
consumption. Since safety is certainly not the only reason that people choose larger vehicles, this is
very much an upper-bound estimate of this effect.

3.7 “Right-sizing” of vehicles
Despite the fact that most light-duty vehicles in the U.S. seat at least four people, the average
occupancy of these vehicles was just 1.67 in 2009 (Davis, Diegel and Boundy, 2012). This slack
capacity implies that if vehicle capacity could be matched to individual trip requirements,
considerable reductions in average energy intensity could be realized. This practice would be
promoted by the availability of some sort of automated carsharing or on-demand mobility model, in
which a traveler requests a vehicle sized to match the needs of a certain trip, and said vehicle
conveniently delivers itself to the traveler.

To assess the potential reductions in energy intensity from this approach, the average energy intensity
under current travel patterns can be compared with that which could result from matching trip-specific
passenger requirements to vehicle size. Based on the 2009 National Household Transportation Survey
(NHTS), the distance-weighted average fuel economy for private vehicle travel was 24.8 MPG (9.50 l
/ 100 km).

One possible scenario is that trips are met with currently-available vehicles. Assume that all private
vehicle trips with 1-2 travelers are met with compact cars (32.1 MPG, 7.33 l / 100 km), those with 3-4
travelers are met with midsize cars (29.4 MPG, 8.00 l / 100 km), and those with 5-7 passengers are
met with minivans (24.2 MPG, 9.72 l / 100 km). Assume that those (very few) trips with more than 7
passengers were met with whichever vehicle that was actually reported by the NHTS respondents (no
right-sizing). This would increase the distance-weighted average fuel economy to 31.3 MPG (7.49 l
/ 100 km), a 21% reduction in energy intensity.

Since many trips are made by single-occupancy vehicles, a more ambitious scenario presupposes the
development of a new class of single-person vehicles. Predicting the fuel consumption of such a
hypothetical vehicle is difficult. However, motorcycles are estimated to consume a little more than
half as much energy per mile as an average car (2881 BTU/mile vs 5342 BTU/mile, per
Transportation Energy Data Book Ed. 31). Let us assume that the hypothetical vehicle would achieve
double the fuel economy of a compact car, holding the level of technological sophistication constant.
Assume further that this hypothetical single-person vehicle serves all trips with a single occupant,
while a compact car serves all trips with two occupants. Again assuming that 3-4 person trips use
midsize cars and 5-7 person trips use minivans, the distance-weighted average fuel consumption
would be reduced by 45% in this case.

While the potential is impressive, it is very optimistic. It considers passenger movement as the only
goal of vehicle travel, ignoring cargo-carrying, towing and other requirements. It omits the above
mentioned safety considerations, but may be more feasible in conjunction with safety-enabled
downsizing. Finally, this approach ignores potential correlations in demand for different vehicle sizes
between different households over time. That is to say, trips requiring large vehicles may be a
relatively small share of the total, but if they tend to occur on certain days or times (e.g. summer long
weekends), the number of large vehicles on the road would not decrease as much.
4 Travel Demand Effects

Despite significant interest in the energy saving benefits of vehicle automation, the potential countervailing energy impacts are often overlooked. Vehicle automation could increase transportation energy consumption by increasing vehicle travel, as a response to a sharp reduction in generalized travel costs for automated vehicles. Travel demand may also grow as automation makes private vehicle travel accessible to demographic groups who do not drive now or drive less. Automation can also allow wider scale adoption of carshare or on-demand mobility services. All of these pathways are represented in our ASIF framework in Eq. 1 through the 'activity' parameter.

4.1 Increased travel due to reduction in generalized costs

Automation can alter the generalized travel costs for driving personal vehicles substantially in three ways. Firstly, vehicle automation (levels 2-4) is expected to substantially reduce accidents on road, 90%-95% of which are caused by driver error (NHTSA, 2008). This should reduce vehicle insurance costs. Secondly, vehicle automation will relieve (to varying degrees, depending on the level of automation) driving related stresses and demands on attention, and thus reduce the 'perceived' discomfort costs of driving. We view this as a reduction in the cost of the driver's travel time, which is one of the largest components in the full generalized cost of travel. Finally, automation reduces per mile energy costs, which is an interaction effect, but is included in our first order calculations.

Beyond reducing driver burden, highly automated vehicles (levels 3-4) can actually permit productive use of in-vehicle time. Therefore the cost of a private driver's travel time, as we know it now, can be substantially altered in automated vehicles, approaching zero in the limiting case of level 4 vehicles. The effects on heavy duty vehicles may also be similar, with reduced energy, insurance and driver related costs playing an important role (for level 4 driver cost could come down to zero), which would make trucking more attractive than other transport modes. Apart from issues of labor relations and industrial organization, the heavy duty assessment is conceptually simpler: driving behavior is more governed by economics, and driver cost is clearly defined by labor costs.

In order to quantify the impact on travel activity, we estimate changes in the various vehicle cost items due to automation and apply published vehicle travel (VMT/VKT) elasticity estimates. Thus, in our ASIF/Kaya computation, activity is endogenously determined from an economic response to estimated shifts in travel cost components, and energy intensity appears both as separate factor I and a variable contributing to the endogenous cost-based determination of activity. There are some risks to this approach for quantifying the effects of high or full automation, since the elasticities are generally estimated over a relatively narrow range of observed costs. The elasticity approach also fails to appreciate the role of travel time budgets (e.g. Schafer et al. (2011) argues that commuting time budget remained constant over centuries). But this is less of an issue for Levels 3-4 since the travel time budget itself is likely to change if in-vehicle time becomes productive.

Estimates for light duty VMT elasticities with respect to generalized travel costs are few. FHWA (2005) suggests a long-run elasticity of -1.0 to -2.0, while Graham and Glaister (2002) recommends -2.3. For heavy vehicles, freight demand elasticities with respect to total costs range from -0.5 to -1.75 (Cambridge Systematics, 2009, Graham and Glaister, 2004, Winebrake et al. 2012), with a choice of -0.97 to -1.0 as a central value by HDR/ICF (2008) and Cambridge Systematics (2009). Since these are long run elasticities, the corresponding changes in travel distance include potential pathways of increased travel such as modal shift from rail and aviation, increased trip frequencies and distances as well as residential and business location choices resulting from reduced generalized costs. We calculate the present day vehicle running and fixed costs for light duty vehicles and heavy duty trucks,
which are presented in Table 2, and apply the elasticities to total costs given posited changes in key cost components.

In order to understand the potential changes due to vehicle automation, we use Celent's (2013) estimate of a 60%-80% reduction in insurance costs resulting from around 90% reduction in accidents. Although it is widely believed that automation will reduce the cost of in-vehicle time, no estimates are available at the moment (Small 2012). We therefore assume a range of 5% (for Level 2) up to 50%-80% (for levels 3 and 4) reduction in cost of travel time. This allows us to modify the generalized travel costs due to vehicle automation and quantify the travel impacts through the following relationship, which is then used to derive the ASIF multiplier for travel activities:

\[
VMT_{auto} = VMT_{pre-auto} \left( \frac{\text{generalized cost}_{auto}}{\text{generalized cost}_{pre-auto}} \right)^{elasticity}
\]  

This results in a wide range of changes, from a 4% increase for low level automation and low elasticities, to a 156% increase for level 4 automation with high elasticities for light duty travel. Reductions in energy intensity could lead to even larger increases in demand via the rebound effect. The large range reflects the uncertainty regarding the changes in the costs of travel time from automation, and the long-run elasticity of travel demand for large changes in generalized cost.

Table 2. Cost components per mile for driving LDVs and HDVs

<table>
<thead>
<tr>
<th>Cost item</th>
<th>2011 Cost per mile (US cents)</th>
<th>Posited 2050 real changes due to vehicle automation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Car</td>
<td>SUV</td>
</tr>
<tr>
<td>Fuel</td>
<td>14.59</td>
<td>19.63</td>
</tr>
<tr>
<td>Maintenance</td>
<td>5.47</td>
<td>6.15</td>
</tr>
<tr>
<td>Accident and Insurance</td>
<td>8.45</td>
<td>8.49</td>
</tr>
<tr>
<td>Wear and ownership</td>
<td>29.91</td>
<td>43.49</td>
</tr>
<tr>
<td>Parking+tolls</td>
<td>2.11</td>
<td>2.27</td>
</tr>
<tr>
<td>Time</td>
<td>49.99</td>
<td>49.99</td>
</tr>
<tr>
<td>Registration</td>
<td>5.15</td>
<td>7.22</td>
</tr>
<tr>
<td>Total</td>
<td>115.67</td>
<td>137.25</td>
</tr>
</tbody>
</table>


4.2 Increased travel due to new user groups

Vehicle automation may increase travel by specific user groups not actively driving, increasing demand beyond that captured by the response of current drivers as in the previous section. Indeed, planners and vehicle manufacturers identify the enhanced mobility for older or driving-restricted demographic groups as a major motivation for automation. There is a noted decline in vehicle license holding and vehicle travel for the elderly, due to both stage-of-life factors and age-induced disabilities which makes driving risky. To bound the increase in travel among these individuals, we consider both the potential for more drivers among the elderly and the young, and for more travel per elderly driver.

\(^2\) note that for this work, we did not modify vehicle purchase costs, as our assumption is a wide-scale adoption of automated vehicles, which will not take place unless vehicle prices are near to current prices in real term.
NHTS (2009) data shows that the age group with the largest fraction of drivers are the 35-55. We assume that automation could lead to the same share of drivers across all age groups (16+). Also, vehicle miles travelled per driver peaks at age 44, then declines steadily through age 62 and more steeply after that. This presumably results from multiple factors, e.g. retirement or reduced working week and age-related disabilities. We assume that the decline between ages 44 and 62 represents the 'natural' rate of decline travel 'needs'. Thus, the accelerated decline per driver after age 62 represents travel that is foregone due to impaired driving abilities. Therefore, the latent demand that could be filled through automation is the difference between the actual age-driving curve and the linear extrapolation of 44-62 trend. As an upper bound, we assume everyone aged 62 and above drive as much as those 62 years old. These result in an increase of 2%-10% in overall personal vehicle travel, after considering the current aggregate age-wise travel distribution.

For heavy duty vehicles, whose primary purpose is to transport goods, automation may create new categories of demand outside those included in the estimated economic response to generalized cost, but we do not identify any here.

4.3 Changes in vehicle ownership and car-sharing models

Car-sharing through commercial car-clubs is becoming increasingly popular, and results in reduced vehicle travel activities by members (Cervero et al. 2007; Martin and Shaheen 2011). However, one impediment to broad adoption of the car-club model is that there is often not enough access to cars to attract new users, and not enough users to justify deploying more cars. Level 4 automation can mitigate this access barrier by allowing vehicles to deliver themselves to the user on-demand, reducing the need for geographic concentration of vehicles. The need to own a vehicle may diminish significantly, and may be entirely, if the availability of such on-demand vehicle can be ensured in future.

Martin and Shaheen (2011) estimate that the net effect of using car-clubs is a reduction of 0.84 t CO2 per household, which represents an 8.8% reduction in CO2, and, by extension, energy use from personal vehicle travel. Given the shared cars are generally more fuel efficient than average household vehicles, the vehicle travel reduction is less than 8.8%. While the final calculations on energy implications will not necessarily be different, we cannot decompose the reported net reduction from car sharing into activity and fuel intensity effects.

The 8.8% reduction in CO2 emissions and energy use is a result of an increase in vehicle travel by previously non-motorized travellers (increase of 0.13 t by 53% of members) and a decrease in travel by those who owned vehicle(s) previously. We therefore estimate that vehicle owners reduced their emissions by 1.93 t ((0.84*100 - 0.13*53)/47), which is around 20% of total emissions and energy use. Although non-vehicle owners may increase their travel, we neglect that impact for our upper bound estimate of 20% reduction. This estimate may reflect self-selection bias (i.e. households which were planning to reduce their travel join the car-clubs) and can inflate the reductions. Therefore, we assume a lower bound of no changes in emissions. Despite the potential decline in vehicle miles, the possibility of increased travel activity cannot be completely ruled out, too, as level 4 automated vehicles would spend some time traveling empty to pick up a passenger.

5 Fuel mix changes

Beyond altering energy demand and emissions through activity, mode share and energy intensity, there is a prospect that automation could alter carbon emissions by changing the carbon intensity of fuels use. If automation promotes low-carbon fuel technologies it would provide a potentially
significant energy-environmental benefit. We have identified three mechanisms by which automation could make advanced alternative fuel technologies (electric vehicles, hydrogen FCVs, or CNG vehicles) more competitive, and possibly speed their introduction. However, the linkages need further study prior to quantification.

First, highly automated vehicles could travel to an alternative fuel station and refuel in unattended mode. This would sharply reduce the user-perceived cost and inconvenience of fuels such as electricity or hydrogen with limited station availability and long refuel/recharge times. These factors, and the implied high cost of the necessarily widespread refueling infrastructure are widely cited as significant barriers to the introduction of alternative fuels (Greene 1998, Nicholas et al. 2004, Welsh 2007, Melaina et al. 2012.) Considering limited station availability alone (not refueling time), Melaina et al. 2012 estimated that the consumer inconvenience for an alternative fuel with very low (1%) station share is equivalent to $1500 to $4000 per vehicle. Fully automated alternative fuel vehicles could largely avoid this penalty.

Second, most low-carbon alternative fuels have low volumetric energy density, and high storage costs (electricity, H2, CNG), leading lower vehicle operating range. Low range is thought to be an important barrier to electric vehicles, for example (NRC 2013). One line of reasoning suggests that automated vehicles by refueling/recharging themselves frequently and automatically, with little user inconvenience, can circumvent this important barrier. A competing argument is that frequently used, shared vehicles might require longer ranges to meet travel demands. It is clear, however, that many proposals for Automated Transit Networks (automated Personal Rapid Transit vehicles) are strongly concluding those systems are well suited to electrification or alternative fuels.

Third, many advanced fuels and vehicles are very capital intensive, involving expensive batteries, fuel-cells, storage tanks, etc. but offering greater energy efficiency and sometimes lower energy-cost per mile. As mentioned earlier, highly automated vehicles may be well suited to the carsharing, or mobility-on-demand service models. Automated shared vehicles are likely to be move from task to task, driven far more miles per year than current private vehicles which spend most of their time parked. Such high-utilization rates call for vehicle types that have low variable operation costs, are durable, more energy efficient, and ideally use lower-cost fuels like electricity or natural gas. Thus automated vehicles that are driven a lot, particularly for carsharing, seem good candidates for high-capital-cost advanced vehicles optimized for high-efficiency, either conventional or alternative fuel drivetrain.

Together these three mechanisms suggest that automation may be favorable to the introduction of advanced and alternative fuels, and may lead to a reduction in fuel emissions intensity, \( F \). We leave quantitative analysis of this topic for separate work.

6 Scenarios and Net Effects

Following the discussions in Sections 3 and 4, Figure summarizes the range of potential impacts for each mechanism. The substantial technical, behavioral, and regulatory uncertainty around vehicle automation mean that it would be unwise to predict the precise impacts of automation on energy consumption in transportation. Several scenarios illustrate how the transportation system might evolve in the coming decades in response to vehicle automation. Rather than being predictions, these scenarios are meant to illustrate how plausible responses to vehicle automation could lead to dramatically different energy and environmental impacts. Table 3 provides a description of each scenario, along with Kaya multipliers corresponding to each of the effects outlined in Sections 3 and
4. The scenarios vary in terms of the levels of automation achieved, effectiveness of the mechanisms listed in Figure 1 in altering energy intensity, the degree of achieved cost reductions (include the cost of driver's travel time), and the magnitude of demand response.

Figure 2 shows the results for the four scenarios, illustrating a broad range of plausible outcomes. In the optimistic “Have our cake and eat it too” scenario, all of the energy intensity benefits develop and travel demand increases only slightly, yielding a 40% reduction in total transportation energy demand. In “Stuck in the middle,” energy intensity benefits are partially offset by higher travel demand, yielding a modest 7% reduction in total energy. In “Strong responses,” all of the envisioned pathways deliver maximum effects, yet these cancel out to leave transportation energy essentially unchanged. “Dystopian nightmare” is a pessimistic case in which no energy intensity improvements actually materialize, but travel time costs fall, travel demand increases significantly, and highway speeds actually increase energy intensity, more than doubling transportation energy demand.

![Figure 1: Summary of energy impacts of vehicle automation through different pathways.](image-url)
Table 3: Description of automation scenarios and estimated Kaya multipliers for each effect.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Description</th>
<th>Platooning</th>
<th>LDV Energy Intensity</th>
<th>LDV Travel Demand</th>
<th>HDV Energy Intensity</th>
<th>HDV Travel Demand</th>
<th>Eco-driving</th>
<th>Crash Avoidance</th>
<th>Rightsizing</th>
<th>Highway Speeds</th>
<th>Generalized Cost</th>
<th>New user groups</th>
<th>Car-sharing</th>
<th>Platooning</th>
<th>Congestion</th>
<th>Generalized Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Have our cake &amp; eat it too</td>
<td>Virtually all of the potential benefits of automation are realized, with little of the downside. Level 3 automation enables much smoother traffic and vastly fewer accidents, all but eliminating congestion. Eco-driving is widely adopted, since it no longer relies on drivers modifying their behaviors. On the highways, speed limits continue to keep traffic to about 70 mph, and platooning is widespread. With drivers largely out of the loop and acceleration no longer important, engine power is greatly dialed back. As accidents become a rarity, vehicles become smaller and shed safety equipment. Despite the reduction in driver burden, people cannot fully disengage from driving tasks, limiting reductions in the costs of drivers’ time.</td>
<td>.75</td>
<td>.96</td>
<td>.80</td>
<td>.77</td>
<td>.95</td>
<td>.55</td>
<td>1.0</td>
<td>1.0</td>
<td>1.6</td>
<td>1.1</td>
<td>0.8</td>
<td>.75</td>
<td>.96</td>
<td>1.4</td>
<td></td>
</tr>
<tr>
<td>Stuck in the middle at Level 2</td>
<td>Automation advances to Level 2, but many states balk at permitting Level 3 and 4 vehicles onto their roads, effectively shutting these vehicles out of the market. Mid-range benefits are obtained from platooning (both LDVs and HDVs) and low-end benefits from eco-driving in LDVs, mainly through driver-coaching systems and energy-saving systems that operate the vehicle in select conditions. Accident rates fall, lowering insurance costs, and more elderly people drive longer, but the cost of in-vehicle time changes only slightly for most drivers.</td>
<td>.86</td>
<td>1.0</td>
<td>.95</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>.83</td>
<td>1.0</td>
<td>1.1</td>
<td></td>
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<tr>
<td>Strong responses</td>
<td>Automation shakes up car travel in a big way. Most of the envisioned responses are large in magnitude – we see big operational improvements and many fewer accidents. Automated eco-driving and platooning take over, and safety equipment and power become much less important. But at the same time, highway speeds increase markedly and travel demand grows substantially due to lower perceived costs of travel. Widespread adoption of mobility-on-demand services means that vehicles are “right-sized” for each trip.</td>
<td>.75</td>
<td>.96</td>
<td>.80</td>
<td>.77</td>
<td>.95</td>
<td>.55</td>
<td>1.2</td>
<td>3.6</td>
<td>1.1</td>
<td>0.8</td>
<td>.75</td>
<td>.96</td>
<td>1.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dystopian nightmare</td>
<td>Broad adoption of Level 4 automation totally redefines what it means to travel by car. Drivers totally disengage from driving responsibilities, and the perceived cost of their time plummets. On the highways, vehicles travel safely at higher speeds, creating continued demand for big, powerful engines. Platooning is forestalled by a regulatory and liability quagmire, and policy inaction. In the cities, congestion relief from operational improvements is swamped by the sheer increase in traffic volume. Automated eco-driving fails to catch on, as drivers value shorter travel times over energy savings. Vehicle designs and ownership models are largely unchanged from today, as consumers buy for their peak requirements.</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.2</td>
<td>2.3</td>
<td>1.1</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.4</td>
<td></td>
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</table>
Figure 2: Changes in energy intensity per kilometer, travel demand, and total energy consumption for light-duty (LDV) and heavy-duty vehicles (HDV) under varying automation scenarios: (1) “Have our cake and eat it too” (2) “Stuck in the middle at Level 2” (3) “Strong responses” (4) “Dystopian nightmare.”
7 Conclusions

Several key insights have emerged. First, vehicle automation offers the potential for substantial reductions in energy consumption and emissions. Second, these reductions are not assured, since they generally are not direct consequences of automation per se. Instead, they follow from other changes in vehicle operations, vehicle design, or transportation system design, which are facilitated by automation. Thirdly, total automobile travel and fuel consumption could increase significantly, if automation sharply reduces the cost of drivers’ time and sufficient energy intensity benefits are not realized.

Among the changes more directly influenced by automation, eco-driving and platooning appear to offer substantial energy intensity reductions: in the range of 5-20% from each, if universally adopted. Congestion reduction, while beneficial for reducing travel time and criteria pollutant emissions, appears to offer relatively limited potential for reducing energy use. Platooning is likely to require some coordination and perhaps regulation to standardize practices, since drag reductions and travel cost savings depend on a vehicle’s separation and position in a platoon.

At relatively low levels of automation, energy intensity savings would most likely outweigh the modest increases in travel. Yet at a high level of automation, different conditions lead to very different outcomes. While it is premature to predict which of our scenarios is more “right” than the others, neither would it be correct to treat them as equally likely. Rather, their variability is instructive, emphasizing both the opportunity for significant energy and transportation benefits, and the need for more careful analysis to identify net effects, and guard against adverse outcomes.

We highlight critical issues and uncertainties regarding the energy implications of automation. The way drivers value their time is crucial to predicting changes in both travel demand and desired highway speeds, but may vary widely around the central value investigated here. The reduction in the cost of driver’s time from automation is similarly important but almost entirely unexplored. We also did not account for competitive responses and any energy/cost reductions in other modes such as air and rail. Finally, automation can enable dramatic shifts in mobility models, vehicle design, fuel choices, and use patterns, but we are only beginning to gather the information to assess how these changes might actually materialize.

References


EPA 2008. Average annual emissions and fuel consumption for gasoline-fueled passenger cars and light trucks, Office of Transportation and Air Quality


