How might automated vehicles affect energy use and emissions?

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Department of Civil & Environmental Engineering
University of Washington
Background:
Energy and emissions implications of AVs
Automation offers substantial energy & environmental benefits...

Travel Demand
Per-mile / per-minute pricing

Design
Right-sizing
Lower performance
Reduced crashworthiness
New vehicle concepts

Fuels
Lower infrastructure costs
Self-refueling

Operations
Platooning
Congestion relief
Traffic smoothing
Eco-driving
Optimal speed/routing

Mode Structure
On-demand mobility
Robo-taxis
Shared vehicles
Personal transit
Occupancy rates

Emissions = Person Miles \cdot \frac{Vehicle Miles}{Person Mile} \cdot \frac{BTUs}{Vehicle Mile} \cdot \frac{Emissions}{BTU}
Automation offers substantial energy & environmental benefits... and risks

<table>
<thead>
<tr>
<th>Travel Demand</th>
<th>Design</th>
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</tr>
</thead>
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<tr>
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<tr>
<td>Underserved populations</td>
<td>Lower performance</td>
<td>Self-refueling</td>
</tr>
<tr>
<td>Lower cost (VOTT)</td>
<td>Reduced crashworthiness</td>
<td></td>
</tr>
<tr>
<td>Land use changes</td>
<td>New vehicle concepts</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
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<td>Emissions = Person Miles * $\frac{Vehicle Miles}{Person Mile} * \frac{BTUs}{Vehicle Mile} * \frac{Emissions}{BTU}$</td>
<td></td>
<td></td>
</tr>
</tbody>
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<table>
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<td>Eco-driving</td>
</tr>
<tr>
<td>Occupancy rates</td>
<td>Optimal speed/routing</td>
</tr>
<tr>
<td>Deadheading</td>
<td>Highway speeds</td>
</tr>
</tbody>
</table>
Right-sizing is largest opportunity

- Platooning
- Congestion mitigation
- Eco-driving
- Higher highway speeds
- Travel cost reduction
- Increased features
- Infrastructure footprint*
- Improved crash avoidance
- De-emphasized performance
- New user groups
- Vehicle right-sizing
- Changed mobility services

% changes in energy consumption due to vehicle automation
Lower cost of travel could swamp gains in efficiency

- Platooning
- Congestion mitigation
- Eco-driving
- Higher highway speeds

**Travel cost reduction**

- Increased features
- Infrastructure footprint*
- Improved crash avoidance
- De-emphasized performance
- New user groups
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- Changed mobility services

Assuming 5-80% lower VOTT, 60-80% lower insurance costs

% changes in energy consumption due to vehicle automation
Scenarios illustrate, but don't quantify, uncertainty
Scenarios illustrate, but don't quantify, uncertainty
Today's focus:
Trying to refine estimates of impacts

1. How does relieving traveler from driving affect value of travel time?

2. How does reduced value of travel time affect residential location choices?

3. How would a right-sized fleet affect fuel economy?
Today's focus:
Trying to refine estimates of impacts

1. How does relieving traveler from driving affect value of travel time?

2. How does reduced value of travel time affect residential location choices?

3. How would a right-sized fleet affect fuel economy?
Automation can make vehicle travel cheaper, safer, and more convenient

"It was the same distance, but the commute felt like it took half the time"

https://www.teslamotors.com/customer-stories/how-autopilot-added-years-my-life
Premise: ridesourcing services provide analogous in-vehicle experience to Level 4-5 AVs

- No need to drive
- Productivity or relaxation
- Ridesourcing is available today
Stated choice experiment elicited marginal utility of time, money

If you had to make a **15-mile commute trip**, which of the following options would you choose?

<table>
<thead>
<tr>
<th>Personal Car</th>
<th>Ride-hailing Service</th>
</tr>
</thead>
<tbody>
<tr>
<td>Travel Time: 20 min</td>
<td>Travel Time: 15 min</td>
</tr>
<tr>
<td>Travel Cost: $5 (fuel, tolls, parking, etc.)</td>
<td>Travel Cost: $15 (fare)</td>
</tr>
<tr>
<td>Waiting Time: 0 min</td>
<td>Waiting Time: 2 min</td>
</tr>
</tbody>
</table>

- Personal Car
- Ride-hailing Service
Respondents were randomly assigned to one of four conditions:

(a) Personal car vs. Human-driven ridesourcing

(b) Personal car vs. Driverless ridesourcing

(c) Personal car vs. Human-driven ridesourcing, multitasking explicitly mentioned

(d) Personal car vs. Driverless ridesourcing, multitasking explicitly mentioned
Conditions (c) and (d) included an activity attribute

If you had to make a **15-mile commute trip**, which of the following options would you choose?

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<td></td>
</tr>
<tr>
<td>Waiting Time: 0 min</td>
<td>Waiting Time: 2 min</td>
</tr>
<tr>
<td>Activity: Driving</td>
<td>Activity: Non-Driving (e.g. work, read, rest, using cellphone...)</td>
</tr>
</tbody>
</table>

- Personal Car
- Ride-hailing Service
Within each condition, we used a full factorial experimental design

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Attribute level(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Travel time car</td>
<td>15 min</td>
</tr>
<tr>
<td></td>
<td>20 min</td>
</tr>
<tr>
<td></td>
<td>25 min</td>
</tr>
<tr>
<td>Travel time ridesourcing</td>
<td>15 min</td>
</tr>
<tr>
<td></td>
<td>20 min</td>
</tr>
<tr>
<td></td>
<td>25 min</td>
</tr>
<tr>
<td>Travel cost car</td>
<td>$5</td>
</tr>
<tr>
<td></td>
<td>$10</td>
</tr>
<tr>
<td></td>
<td>$15</td>
</tr>
<tr>
<td>Travel cost ridesourcing</td>
<td>$10</td>
</tr>
<tr>
<td></td>
<td>$15</td>
</tr>
<tr>
<td></td>
<td>$20</td>
</tr>
<tr>
<td>Waiting time car</td>
<td>0 min</td>
</tr>
<tr>
<td>Waiting time ridesourcing</td>
<td>2 min</td>
</tr>
</tbody>
</table>
Survey was hosted on SurveyMonkey, respondents recruited through Amazon MTurk

- 535 respondents, 502 valid responses

- 6 choice situations each → 3012 observations
We used binary mixed logit to model utility of alternatives

\[ U_{ij,\text{car}} = \beta_1\text{cost}_{j,\text{car}} + \beta_2\text{car}time_{j,\text{car}} + \varepsilon_{ij,\text{car}} \]

\[ U_{ij,\text{RS}} = \alpha_i + \beta_1\text{cost}_{j,\text{RS}} + \beta_2\text{RS}time_{j,\text{RS}} + \beta_3\text{driverless}_{j,\text{RS}} + \beta_4\text{multitask}_{j,\text{RS}} + \beta_5\text{driverless}_{j,\text{RS}}time_{j,\text{RS}} + \beta_6\text{multitask}_{j,\text{RS}}time_{j,\text{RS}} + \varepsilon_{ij,\text{RS}} \]

\( i \): individuals

\( j \): choice situations
Value of travel time is lower in ridesourcing services than when driving self

![Graph showing the value of travel time in ridesourcing services compared to driving self. The value is lower by 16% on average.]
Value of time increases with automation; Decreases with multitasking
Conclusions

• Implied disutility to AV travel

• Value of time in ridesourcing 13-45% lower than driving

1. How does relieving traveler from driving affect value of travel time?

2. How does reduced value of travel time affect residential location choices?

3. How would a right-sized fleet affect fuel economy?
On-demand mobility services and self-driving cars → free the traveler from the effort of driving, which is expected to reduce the perceived cost of travel time.

**Magic Carpet**: an arbitrary technology that makes travel radically more comfortable and convenient and requires little to no active control from the traveler.
Goal: Explore how reductions in the perceived cost of travel time may affect the attractiveness of different neighborhoods in a region

- Puget Sound (Washington) region as a case study.

- Estimated a **multinomial logit residential location choice model** that incorporated travel time via two measures of accessibility

- Explored how changes in the cost of travel time might change land use patterns in that region.
Overview of the model
We used two measures of accessibility

It depends on:

> **How long** it takes for residents to get to **work**,  
> The **available** transportation options,  
> Accessible opportunities in each zone (captured by number of retail jobs in each zone)

**logsum** measure for commute accessibility

**gravity-based** measure for regional accessibility
Data Sources for accessibility

- Destination choices
- Number of jobs
- Travel time and distance
- Income

Regional accessibility
Data Sources for accessibility

- Destination choices
- Number of jobs
- Travel time and distance
- Income
- Mode choices

Regional accessibility
Commute accessibility
Data Sources for residential location choice model

- **Neighborhood**
  - School quality
  - Density
    - Average Housing Price
    - Average sq Footage
    - Having children

- **House**
  - House
    - Average sq Footage
    - Having children

- **Household**
  - Household
    - Income

- **Sources**
  - Great Schools
  - United States Census Bureau
  - Zillow
  - Puget Sound Regional Council

- **University of Washington**
  - Civil & Environmental Engineering
We investigated effects of changing time cost of travel

• Cut cost of travel time by half.
  – Reduction in value of travel time
  – Magic carpets being a faster mode compared with cars
  – Combination of both

The choice of 50% is arbitrary and is for the purpose of exploring the methodology and observing the impact of the hypothetical magic carpet.
We tested two scenarios

1) Magic carpets replace cars
   - The time cost of travel is reduced by half
   - short run financial cost of magic carpet travel is same as for cars ($0.10/mile)

2) Magic carpets are introduced as an additional mode available to all people as an on-demand service
   - The time cost of travel is reduced by half
   - price of the magic carpet service is $0.50 / mile,
Changes in commute accessibility with respect to base accessibility

<table>
<thead>
<tr>
<th>Magic carpets replace private cars</th>
<th>Magic carpets as an additional service</th>
</tr>
</thead>
</table>

![Map showing changes in commute accessibility with magic carpets as an additional service compared to private cars.](image_url)
Changes in log of regional accessibility with respect to base accessibility

<table>
<thead>
<tr>
<th>Magic carpets replace private cars</th>
<th>Magic carpets as an additional service</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Map of Magic carpets replace private cars" /></td>
<td><img src="image2.png" alt="Map of Magic carpets as an additional service" /></td>
</tr>
</tbody>
</table>
Changes in residential location demand, holding prices constant

<table>
<thead>
<tr>
<th>Magic carpets replace private cars</th>
<th>Magic carpets as an additional service</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;5000</td>
<td>&lt;-5000</td>
</tr>
<tr>
<td>-5000- -1500</td>
<td>-5000- -1500</td>
</tr>
<tr>
<td>-1500- 0</td>
<td>-1500- 0</td>
</tr>
<tr>
<td>0- 1500</td>
<td>0- 1500</td>
</tr>
<tr>
<td>1500- 5000</td>
<td>1500- 5000</td>
</tr>
<tr>
<td>5000- 10000</td>
<td>5000- 10000</td>
</tr>
<tr>
<td>10000&lt;</td>
<td>10000&lt;</td>
</tr>
</tbody>
</table>
Magic carpets replace private cars → shift population to the urban fringes,

Magic carpets as an additional on-demand service → increase the attractiveness of living in central cities
Reflections and Limitations

• Many uncertainty sources

• The results of this analysis are strongly dependent on multiple layers of models

• Many model specifications returned nonsensical results

1. How does relieving traveler from driving affect value of travel time?

2. How does reduced value of travel time affect residential location choices?

3. How would a right-sized fleet affect fuel economy?
Fuel economy & GHG standards are based on vehicle footprint (Cars)

\[
\text{Standard} = \frac{\sum_i \text{Sales}_i \cdot f(\text{footprint}_i)}{\sum_i \text{Sales}_i}
\]

Figure I.1 CO₂ (g/mile) Passenger Car Standards Curves

Figure I.2 \( \text{CO}_2 \) (g/mile) Light Truck Standards Curves

\[
\text{Standard} = \frac{\sum_i \text{Sales}_i \cdot f(\text{footprint}_i)}{\sum_i \text{Sales}_i}
\]

We assume that vehicle size matches travel party size, for mobility services.

<table>
<thead>
<tr>
<th>Avg Footprint</th>
<th>2016 Standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 ft²</td>
<td>41 mpg</td>
</tr>
<tr>
<td>43 ft²</td>
<td>39 mpg</td>
</tr>
<tr>
<td>48 ft²</td>
<td>36 mpg</td>
</tr>
<tr>
<td>56 ft²</td>
<td>28 mpg</td>
</tr>
</tbody>
</table>
Mobility services providers are already starting to right-size
Mix of travel party sizes depends on day, time, location

National Minutes of Demand by Day

Data source: National Household Travel Survey 2009

Total Minutes of Demand (Millions)

Time of Week

- Sunday
- Monday
- Tuesday
- Wednesday
- Thursday
- Friday
- Saturday

1 Passenger
2 Passenger
3 Passenger
4 Passenger
5 Passenger
6 Passenger
7 Passenger
We considered two approaches to right-sizing fleet

1. Minimize number of vehicles
   (larger vehicles sometimes move smaller parties)

\[
\text{Number of } n - \text{seat Vehicles} = \max(\sum_{i=n}^{7} X_{it}) - \max(\sum_{i=n+1}^{7} X_{it})
\]

2. Minimize number of seats
   (vehicle size matches party size for each trip)

\[
\text{Number of } n - \text{seat Vehicles} = \max(X_{nt})
\]
Right-sizing fleet would increase MPG standard 20% above actual 2016 sales mix

2016 sales-weighted CAFE standard for National right-sized mix = 39.1 – 39.4 mpg

2016 sales-weighted CAFE standard for actual size mix = 32.7 mpg
Many unanswered questions about right-sizing

• Market potential for micromobility?

• Social optimum vs market equilibrium?

• Asymmetry between costs of providing larger vehicles and opportunity costs of unfulfilled requests?

• Willingness of travelers to split parties?

Thank you!

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@DonMacKenzie9
Appendix slides follow
Waymo has reduced disengagement rate 90% in 3-4 years

GM has reduced disengagement rate 99% in 2 years, now 1-2 years behind Waymo

Waymo's estimated crash rate is ~ 10X human crash rate

**About 20% of disengagements in 2015 would have resulted in a crash.**

http://fortune.com/2016/01/13/google-self-driving-car-accidents/

<table>
<thead>
<tr>
<th></th>
<th>Miles between incidents</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uber, all disengagements (March 2018)</td>
<td>13</td>
</tr>
<tr>
<td>GM Cruise, safety disengagements (2018)</td>
<td>5,000</td>
</tr>
<tr>
<td>Waymo, safety disengagements (2018)</td>
<td>10,000</td>
</tr>
<tr>
<td>Waymo, crashes (estimated, 2018)</td>
<td>50,000</td>
</tr>
<tr>
<td>Human drivers, crashes (2015)</td>
<td>490,000</td>
</tr>
</tbody>
</table>

Extrapolating…
Crash rate might be competitive with human drivers in 4-10 years

http://fortune.com/2016/01/13/google-self-driving-car-accidents/
https://www.fhwa.dot.gov/policyinformation/statistics/2015/xls/vmt421c.xls
https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/812318
http://www.thedrive.com/tech/18150/waymo-self-driving-cars-are-the-most-competent-ca-reports-say
Market intro. to peak growth is ~10 years, could be ~5 years by 2030

New automotive features rarely grow by more than 10% per year

It will be decades before all vehicles can drive themselves.

Fleet Turnover
- 60% of cars last 15+ years
- Average US car is 11 years old

Percentage of New Cars Equipped

- 0%
- 20%
- 40%
- 60%
- 80%
- 100%
Driver’s time is single largest cost, for both light and heavy duty vehicles.

<table>
<thead>
<tr>
<th></th>
<th>Cars</th>
<th>Light Duty Trucks</th>
<th>Heavy Duty Truck</th>
</tr>
</thead>
<tbody>
<tr>
<td>Driver's time</td>
<td>$0.50</td>
<td>$0.50</td>
<td>$0.61</td>
</tr>
<tr>
<td>Wear &amp; Ownership</td>
<td>$0.30</td>
<td>$0.43</td>
<td>$0.19</td>
</tr>
<tr>
<td>Fuel</td>
<td>$0.15</td>
<td>$0.20</td>
<td>$0.59</td>
</tr>
<tr>
<td>Insurance &amp; Accidents</td>
<td>$0.08</td>
<td>$0.08</td>
<td>$0.07</td>
</tr>
<tr>
<td>Maintenance</td>
<td>$0.05</td>
<td>$0.06</td>
<td>$0.19</td>
</tr>
<tr>
<td>Registration &amp; Fees</td>
<td>$0.05</td>
<td>$0.07</td>
<td>$0.06</td>
</tr>
<tr>
<td>Parking</td>
<td>$0.02</td>
<td>$0.02</td>
<td>$0.00</td>
</tr>
<tr>
<td><strong>Generalized Cost per Mile</strong></td>
<td><strong>$1.16</strong></td>
<td><strong>$1.37</strong></td>
<td><strong>$1.71</strong></td>
</tr>
</tbody>
</table>
Travel demand impacts were estimated using a generalized cost approach.

- Elasticity of travel demand w.r.t. generalized cost: -1.0
  - For both LDV and HDV

- Assumed cost reductions through automation:

<table>
<thead>
<tr>
<th></th>
<th>Insurance Costs</th>
<th>Driver’s Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Driver assist</td>
<td>60%</td>
<td>0-5%</td>
</tr>
<tr>
<td>Full automation</td>
<td>80%</td>
<td>50-80%</td>
</tr>
</tbody>
</table>

\[ VKT_{auto} = VKT_{pre-auto} \left( \frac{\text{generalized cost}_{auto}}{\text{generalized cost}_{pre-auto}} \right)^{\text{elasticity}} \]
PSRC has simulated travel demand impacts for Seattle region

<table>
<thead>
<tr>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
<th>Scenario 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;AVs increase network capacity.&quot;</td>
<td>&quot;Important trips are in AVs&quot;</td>
<td>&quot;Everyone who owns a car owns an AV.&quot;</td>
<td>&quot;All autos are automated, with all costs of auto use passed onto the user.&quot;</td>
</tr>
<tr>
<td>30% capacity increase on freeways, major arterials</td>
<td>30% capacity increase on freeways, major arterials</td>
<td>30% capacity increase on freeways, major arterials</td>
<td></td>
</tr>
<tr>
<td>Travel time is perceived at 65% of actual travel time for high value of time household trips (&gt;24/hr.)</td>
<td>Travel time is perceived at 65% of actual travel time for all trips</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50% parking cost reduction</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Cost per mile is $1.65

+3.6%  +5.0%  +19.6%  -35.4%
ARC has simulated impacts for Atlanta region

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Capacity +50%</th>
<th>Value of Time -50%</th>
<th>Operating Cost -71%</th>
<th>Parking Cost -100%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>12.1%</td>
<td>23.8%</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>12.2%</td>
<td>23.9%</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.9%</td>
<td>3.6%</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>-8.7%</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Harb et al. gave people chauffeurs to simulate owning a driverless car.

With chauffeurs, there was an 80% increase in VMT compared to non-chauffeur weeks. This increase was observed across different groups: retirees, families, millennials, and the entire sample. The study by Mustapha Harb, Yu Xiao, Giovanni Circella, Patricia Mokhtarian, and Joan Walker, TRB Paper No. 18-06407, Projecting Travelers into a World of Self-Driving Cars: Naturalistic Experiment for Travel Behavior Implications.
(Full) Automation makes mobility services more feasible, and more essential

- Platooning
- Congestion mitigation
- Eco-driving
- Higher highway speeds
- Travel cost reduction
- Increased features
- Infrastructure footprint*
- Improved crash avoidance
- De-emphasized performance
- New user groups
- Vehicle right-sizing

**Changed mobility services**

% changes in energy consumption due to vehicle automation
The hope is that lower total costs will induce shift to mobility services and fewer trips, but…

(a) Future competitive situation - Urban setting.

Questions for you

• How many of you have a phone plan?
  – X minutes, Y GB per month

• How many of you are on a pay-as-you-go plan?
  – $X / minute, $Y / MB?

• Why?
Lyft’s monthly subscription plan is expanding — and now has a waitlist

$200 a month for $15 off 30 rides

By Andrew J. Hawkins | @andyjayhawk | May 9, 2018, 2:06pm EDT

spend up to $450 on ride-hailing a month. One all-access pass offered up to 30 standard Lyft rides for $199 a month, another was priced at $300, and another at $399 for 60 rides.
Mobility services appear to be the key to unlocking many benefits of automation.
Questions for you

• How many of you have used Uber, Lyft, or a similar service?

• How many of you have used UberPool, Lyft Line, or a similar service?

• Why?
By reducing total cost of mobility services, automation reduces incentive to share rides

Emerging work by David R. Keith & Sergey Naumov (MIT) suggests lower market share for pooling.

<table>
<thead>
<tr>
<th>Utility Attribute</th>
<th>MyRider</th>
<th>RiderPool</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Trip Price</td>
<td>$11.25</td>
<td>$6.75</td>
</tr>
<tr>
<td>Pick Up Time</td>
<td>3 min</td>
<td>7 min</td>
</tr>
<tr>
<td>Travel Time</td>
<td>16 min</td>
<td>16-24 min</td>
</tr>
</tbody>
</table>

![Graphs showing travel cost and market share over years]
Mobility services require L4-5 automation

% changes in energy consumption due to vehicle automation

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- Congestion mitigation
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SAE Level

2
3
4
5
Shared mobility fleets should have fewer emission-intensive cold starts

- Rule of thumb:
  - “80% in first 30 seconds, 90% in first 5 minutes”

### TABLE 5 Comparison of Emissions from Initial Engine Start and Restart

<table>
<thead>
<tr>
<th></th>
<th>Tier 2-Bin 5 (15)a</th>
<th>Initial Engine Start</th>
<th>Engine Restart</th>
</tr>
</thead>
<tbody>
<tr>
<td>THC (mg)</td>
<td>878</td>
<td>191</td>
<td>44</td>
</tr>
<tr>
<td>NO_x (mg)</td>
<td>552</td>
<td>228</td>
<td>6</td>
</tr>
<tr>
<td>CO (mg)</td>
<td>31290</td>
<td>2970</td>
<td>1253</td>
</tr>
</tbody>
</table>

*a Tier 2-Bin 5 g/mi converted to FTP-75 mg

We spend a lot of **time** in traffic, but don't travel a lot of **miles** in traffic

Estimates of wasted fuel from TTI Urban Mobility Report, as % of on-highway gasoline & diesel
Unconstrained by driver reaction times, highway speeds could increase.
Platooning could reduce energy intensity in near term


Figure 11: Results for 4-vehicle platoon
Could automation mean a ceasefire in the horsepower wars?

Without crash risk, could we remove safety equipment? Get everyone into a compact car?

With more free time, travelers may demand more comfort & convenience features

Some of our impacts may be different for EVs than for conventional vehicles

EV efficiency is less sensitive than ICEs to engine speed and load. So...

EVs likely to be more sensitive to highway speeds and platooning effects.

EVs likely to be less sensitive to congestion relief and eco-driving.

Sensitivity to changes in acceleration performance…???

Conditions (c) and (d) included additional text in description of mode alternatives

- “You will have the option of doing other tasks (e.g. working, reading, watching videos, texting, etc.) or just relaxing during the trip, because you don’t need to pay attention to driving”.

- “A driverless ride-hailing service is similar to services offered by Uber and Lyft, where you can request a ride using an application on your smartphone, but the car will be driven by the computer rather than a human driver”
## Regression results: car vs ridesourcing

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Model 1</th>
<th>Model 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>InterceptRHS</td>
<td></td>
<td>-0.8973 *</td>
<td>-0.8604 *</td>
</tr>
<tr>
<td>SdIntercept</td>
<td></td>
<td>-0.1169</td>
<td>-0.1124</td>
</tr>
<tr>
<td>Cost</td>
<td></td>
<td>-0.1517 ***</td>
<td>-0.1516 ***</td>
</tr>
<tr>
<td>TimeDrive</td>
<td>Travel time of personal car</td>
<td>-0.0619 ***</td>
<td>-0.0620 ***</td>
</tr>
<tr>
<td>TimeRHS</td>
<td>Travel time of RHS</td>
<td>-0.0516 ***</td>
<td>-0.0536 **</td>
</tr>
<tr>
<td>DriverlessRHS</td>
<td>(Binary, Associated with RHS) 1: Driverless; 0: Regular</td>
<td>-0.2282 *</td>
<td>0.1060</td>
</tr>
<tr>
<td>MultitaskingRHS</td>
<td>(Binary, Associated with RHS) 1: Explicit mention of multitasking; 0: otherwise</td>
<td>0.263 **</td>
<td>0.1289 **</td>
</tr>
<tr>
<td>TimeDriverlessRHS</td>
<td>Travel time for driverless RHS</td>
<td>-</td>
<td>-0.0171 *</td>
</tr>
<tr>
<td>TimeMultitaskingRHS</td>
<td>Travel time of RHS in cases where multitasking is mentioned explicitly</td>
<td>-</td>
<td>0.0200 *</td>
</tr>
<tr>
<td>Log-likelihood</td>
<td></td>
<td>-1427.6</td>
<td>-1427.0</td>
</tr>
<tr>
<td>Null Model Log-likelihood</td>
<td></td>
<td>-1623.4</td>
<td>-1623.4</td>
</tr>
<tr>
<td>Rho-Squared</td>
<td></td>
<td>0.1206</td>
<td>0.1210</td>
</tr>
<tr>
<td>Adjusted Rho-Squared</td>
<td></td>
<td>0.1191</td>
<td>0.1190</td>
</tr>
<tr>
<td>No. of Observations</td>
<td></td>
<td>3012</td>
<td>3012</td>
</tr>
</tbody>
</table>

0 ‘***’ 0.001 ‘**’ 0.01 ‘*’
## Multinomial logit model results:

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficient Estimate</th>
<th>Standard Error</th>
<th>t-value</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zestimate / Income / AvgSqFt</td>
<td>-4.71</td>
<td>2.48</td>
<td>-1.90</td>
<td>0.06</td>
</tr>
<tr>
<td>SchoolQuality*Child</td>
<td>0.0582</td>
<td>0.0221</td>
<td>2.63</td>
<td>0.01</td>
</tr>
<tr>
<td>ln(Gaccess)</td>
<td>1.27</td>
<td>0.118</td>
<td>10.74</td>
<td>0.00</td>
</tr>
<tr>
<td>Logsum</td>
<td>2.70</td>
<td>0.0511</td>
<td>52.86</td>
<td>0.00</td>
</tr>
<tr>
<td>WorkplaceDummy</td>
<td>2.06</td>
<td>0.111</td>
<td>18.49</td>
<td>0.00</td>
</tr>
<tr>
<td>Density</td>
<td>15.8</td>
<td>7.27</td>
<td>2.18</td>
<td>0.00</td>
</tr>
<tr>
<td>ln(Gaccess)^2</td>
<td>0.0736</td>
<td>0.00613</td>
<td>12.01</td>
<td>0.00</td>
</tr>
<tr>
<td>Logsum^2</td>
<td>0.0819</td>
<td>0.00238</td>
<td>34.38</td>
<td>0.00</td>
</tr>
<tr>
<td>SchoolQuality</td>
<td>0.0475</td>
<td>0.0109</td>
<td>4.37</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Null Log Likelihood: -13621.4
Final Log Likelihood: -10126.808
AIC: 20271.616
BIC: 20327.483
Mode choice model

\[ A_{ij} = \ln \left[ \sum_{c \in C_{ij}} \exp(V_{cij}) \right] \]
\[ V_{cij} = \beta_{0c} + \beta_1 \left( \frac{\text{cost}_{cj}}{\text{income}_i} \right) + \beta_{2c} \times TTT_{cj} \]

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficient Estimate</th>
<th>Standard Error</th>
<th>T</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transit Intercept</td>
<td>-1.13</td>
<td>0.116</td>
<td>-9.73</td>
<td>0.00</td>
</tr>
<tr>
<td>Walking Intercept</td>
<td>1.48</td>
<td>0.204</td>
<td>10.05</td>
<td>0.00</td>
</tr>
<tr>
<td>Cost / Income</td>
<td>-37.2</td>
<td>5.24</td>
<td>-7.10</td>
<td>0.00</td>
</tr>
<tr>
<td>Total Travel Time Car</td>
<td>-0.0161</td>
<td>0.00478</td>
<td>-3.36</td>
<td>0.00</td>
</tr>
<tr>
<td>Total Travel Time Transit</td>
<td>-0.000377</td>
<td>0.00117</td>
<td>-0.32</td>
<td>0.75</td>
</tr>
<tr>
<td>Total Travel Time Walking</td>
<td>-0.0844</td>
<td>0.00568</td>
<td>-14.86</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Initial Log Likelihood: -3002.171
Final Log Likelihood: -1775.045
AIC: 3562.091
BIC: 3599.915

Note: Car Intercept fixed at zero for identification purposes
\[ A_{ij}^{Ret} = \frac{1}{N} \sum_{k=1}^{N} \left( \frac{(Number \ of \ retail \ jobs_k)^{\gamma_{Ret}}}{(Impedance_{jk})^{\beta_{Ret}}} \right) \]

\[ V_{ijk}^{Ret} = \gamma_{Ret} \cdot ln (number \ of \ jobs_k) - \beta_{Ret} \cdot ln (impedance_{ijk}) \]

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
<th>Std err</th>
<th>t-test</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma_{retail}$ (log of number of retail jobs)</td>
<td>0.22</td>
<td>0.0406</td>
<td>5.43</td>
<td>0.00</td>
</tr>
<tr>
<td>$\beta_{retail}$ (log of impedance)</td>
<td>3.87</td>
<td>0.102</td>
<td>37.91</td>
<td>0.00</td>
</tr>
<tr>
<td>$\beta$ (transit weight)</td>
<td>1.03</td>
<td>0.0249</td>
<td>41.38</td>
<td>0.00</td>
</tr>
<tr>
<td>$\gamma$ (walking weight)</td>
<td>0.715</td>
<td>0.0302</td>
<td>23.69</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Init log likelihood: -14366.327
Final log likelihood: -4014.462
AIC: 8036.923
BIC: 8064.881
The equivalent changes in price($)/SqFt to maintain utility in each tract the same

<table>
<thead>
<tr>
<th>Magic carpets replace private cars</th>
<th>Magic carpets as an additional service</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;50</td>
<td>&lt;50</td>
</tr>
<tr>
<td>50-100</td>
<td>50-100</td>
</tr>
<tr>
<td>100-150</td>
<td>100-150</td>
</tr>
<tr>
<td>150-200</td>
<td>150-200</td>
</tr>
<tr>
<td>200&lt;</td>
<td>200&lt;</td>
</tr>
</tbody>
</table>
Magic carpets replace private cars ≡ an average reduction of $126/sqft, Magic carpets as an additional new on-demand service ≡ an average reduction of $188/sqft.