Autonomous Vehicles

Seminar: Digitalisation and the Rebound Effect

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28/10/2020
Content

Many concepts around autonomous vehicles:

• Safety
• Liability
• Technology
• Societal
• Infrastructure
• Economics
• Ecological
Many concepts around autonomous vehicles:

- Safety
- Liability
- Technology
- Societal
- Infrastructure
- Economics
- Ecological

Structure of this talk is heavily derived from Austin Brown et al. *An Analysis of Possible Energy Impacts of Automated Vehicles* [1] because they try to quantify different ecological aspects with the same baseline
Content

- Framework to quantify effects
- Individual Effects
- Widespread adaptation
- Wider context
## Autonomous Driving

<table>
<thead>
<tr>
<th>SAE Level</th>
<th>Name</th>
<th>Narrative Definition</th>
<th>Execution of Steering and Acceleration/Deceleration</th>
<th>Monitoring of Driving Environment</th>
<th>Feedback Performance of Dynamic Driving Task</th>
<th>System Capability (Driving Modes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>No Automation</td>
<td>the full-time performance by the human driver of all aspects of the dynamic driving task, even when enhanced by warning or intervention systems.</td>
<td>Human driver</td>
<td>Human driver</td>
<td>Human driver</td>
<td>n/a</td>
</tr>
<tr>
<td>1</td>
<td>Driver Assistance</td>
<td>the driving mode-specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the human driver perform all remaining aspects of the dynamic driving task.</td>
<td>Human driver and system</td>
<td>Human driver</td>
<td>Human driver</td>
<td>Some driving modes</td>
</tr>
<tr>
<td>2</td>
<td>Partial Automation</td>
<td>the driving mode-specific execution by one or more driver assistance systems of both steering and acceleration/deceleration using information about the driving environment and with the expectation that the human driver perform all remaining aspects of the dynamic driving task.</td>
<td>System</td>
<td>Human driver</td>
<td>Human driver</td>
<td>Some driving modes</td>
</tr>
</tbody>
</table>

### Automated driving system ("system") monitors the driving environment

<table>
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<tr>
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<th>System Capability (Driving Modes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Conditional Automation</td>
<td>the driving mode-specific performance by an automated driving system of all aspects of the dynamic driving task with the expectation that the human driver will respond appropriately to a request to intervene.</td>
<td>System</td>
<td>System</td>
<td>Human driver</td>
<td>Some driving modes</td>
</tr>
<tr>
<td>4</td>
<td>High Automation</td>
<td>the driving mode-specific performance by an automated driving system of all aspects of the dynamic driving task, even if the human driver does not respond appropriately to a request to intervene.</td>
<td>System</td>
<td>System</td>
<td>System</td>
<td>Some driving modes</td>
</tr>
<tr>
<td>5</td>
<td>Full Automation</td>
<td>the full-time performance by an automated driving system of all aspects of the dynamic driving task under all roadway and environmental conditions that can be managed by a human driver.</td>
<td>System</td>
<td>System</td>
<td>System</td>
<td>All driving modes</td>
</tr>
</tbody>
</table>

Note: Other sources classify AVs from L0 to L4. Slides are self contained.
### Assumptions:
- L5 automation
- AVs are not electric
- Connected and coordinated
- Disregard periods of L0 - L4
- Include period where L5 coexists with CVs

**CV:** Conventional vehicle  
**AV:** Autonomous vehicle

**Note:** Other sources classify AVs from L0 to L4

Slides are self contained
Quantifying ecological impact: Kaya identity

\[ F = P \times \frac{G}{P} \times \frac{E}{G} \times \frac{F}{E} \]

F: Global CO2 emission
G: GDP
P: Population
E: Energy Consumption
Framework

Quantifying ecological impact: Kaya identity

\[ F = P \times \frac{G}{P} \times \frac{E}{G} \times \frac{F}{E} \]

Energy per unit GDP (Energy Intensity)

Carbon per unit Energy (Carbon Intensity)

F: Global CO2 emission
G: GDP
P: Population
E: Energy Consumption

[1] [29]
Modifying Kaya identity to AVs

1) Replace CO2 usage with liquid fuel usage
2) Split up identity to AVs and CVs

\[ \text{Liquids} = \text{Liquids}_{AV} + \text{Liquids}_{CV} \]
Modifying Kaya identity to AVs

\[
\text{Liquids} = \text{Liquids}_{AV} + \text{Liquids}_{CV}
\]

\[
\text{Liquids} = \#\text{vehicles} \times \left( k \times \frac{VMT_{AV}}{AVs} \times \frac{E_{AV}}{VMT_{AV}} \times \frac{\text{Liquids}_{AV}}{E_{AV}} + (1 - k) \times \frac{VMT_{CV}}{CVs} \times \frac{\text{Liquids}_{CV}}{VMT_{CV}} \times \frac{\text{Liquids}_{CV}}{E_{CV}} \right)
\]

k: fraction of AVs
VMT: vehicle miles traveled
E: energy use
AVs/CVs: number of vehicles
#vehicles: number of vehicles
Modifying Kaya identity to AVs

\[
\text{Liquids} = \#\text{vehicles} \times \left( k \times \frac{\text{VMT}_{AV}}{\text{AVs}} \times \frac{E_{AV}}{\text{VMT}_{AV}} \times \frac{\text{Liquids}_{AV}}{E_{AV}} + (1 - k) \times \frac{\text{VMT}_{CV}}{\text{CVs}} \times \frac{\text{Liquids}_{CV}}{\text{VMT}_{CV}} \times \frac{\text{Liquids}_{CV}}{E_{CV}} \right)
\]

- $k$: fraction of AVs
- VMT: vehicle miles traveled
- E: energy use
- AVs/CVs: number of vehicles
- #vehicles: number of vehicles

Mistake by the authors?

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[1]
Framework

Modifying Kaya identity to AVs

We care about 3 quantities: UI, EI and FI (for AV and CV)

\[
\text{Liquids} = \#\text{vehicles} \times \left( k \times \frac{VMT_{AV}}{AVs} \right) \times \frac{E_{AV}}{VMT_{AV}} \times \frac{\text{Liquids}_{AV}}{E_{AV}} + (1 - k) \times \frac{VMT_{CV}}{CVs} \times \frac{\text{Liquids}_{CV}}{VMT_{CV}} \times \frac{\text{Liquids}_{CV}}{E_{CV}}
\]

UI: Use intensity  
FI: Fuel intensity  
EI: Energy Intensity
Modifying Kaya identity to AVs

We care about 3 quantities: UI, EI and FI (for AV and CV)
Many concepts are connected, analysis tries to isolate and quantify them
Presentation does not include every element of [1] so conclusion values differ

\[
\text{Liquids} = \#\text{vehicles} \times \left( k \times \frac{VMT_{AV}}{AVs} \times \frac{E_{AV}}{VMT_{AV}} \times \frac{\text{Liquids}_{AV}}{E_{AV}} + (1-k) \times \frac{VMT_{CV}}{CVs} \times \frac{\text{Liquids}_{CV}}{VMT_{CV}} \times \frac{\text{Liquids}_{CV}}{E_{CV}} \right)
\]

UI: Use intensity
FI: Fuel intensity
EI: Energy Intensity
Content

- Framework to quantify effects
- Individual Effects
- Widespread adaptation
- Wider context
Individual Effects

Assume mix of Level 5 AVs and CVs on the roads

Content:

- Efficient driving
- Platooning
Individual Effects

Efficient driving

AVs are able to drive more efficient by planning ahead when to accelerate and decelerate based on road layout, road signs, and traffic conditions. They don’t drive abruptly or aggressively.
Efficient driving

AVs are able to drive more efficient by planning ahead when to accelerate and decelerate based on road layout, road signs, and traffic conditions. They don’t drive abruptly or aggressively.

**Eco driving** means by [6] [8]:

- Anticipate traffic flow and signals
- Drive with *correct* speed
- Regular vehicle maintenance such as checking tyre pressure
- Eliminate stop and go driving

- Already present in modern cars:
  - Slow acceleration (shift between 2000-2500 RPMs)
  - Eliminate excessive idling
Individual Effects

Efficient driving

15% EI (energy intensity: Energy/VMT) saved by [1] up to 10% fuel savings according to [6]
15% fuel savings according to [7] without lower travel times
[8] even claims 30% fuel savings for autonomous vehicles
Platooning

In cycling riders form platoons (peloton) and regularly switch the head cyclist to reduce aerodynamical drag on the group.

Example of platoons in cycling time trials

Drag for different lengths of platoons with a fixed wheel to wheel distance

<table>
<thead>
<tr>
<th>Length (m)</th>
<th>EI (%)</th>
<th>UI (%)</th>
<th>FI (%)</th>
<th>AVG (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>100%</td>
<td></td>
<td></td>
<td>100%</td>
</tr>
<tr>
<td>0.04</td>
<td>97.6%</td>
<td>64.1%</td>
<td></td>
<td>80.9%</td>
</tr>
<tr>
<td>0.03</td>
<td>97.2%</td>
<td>61.7%</td>
<td>51.7%</td>
<td>70.2%</td>
</tr>
<tr>
<td>0.02</td>
<td>97.1%</td>
<td>61.2%</td>
<td>49.5%</td>
<td>63.4%</td>
</tr>
<tr>
<td>0.01</td>
<td>97.1%</td>
<td>61.1%</td>
<td>49.1%</td>
<td>58.9%</td>
</tr>
<tr>
<td>0.005</td>
<td>97.1%</td>
<td>61.0%</td>
<td>48.9%</td>
<td>55.8%</td>
</tr>
<tr>
<td>0.001</td>
<td>97.0%</td>
<td>61.0%</td>
<td>48.8%</td>
<td>53.4%</td>
</tr>
<tr>
<td>0.0005</td>
<td>97.0%</td>
<td>61.0%</td>
<td>48.6%</td>
<td>51.6%</td>
</tr>
<tr>
<td>0.00005</td>
<td>97.0%</td>
<td>61.0%</td>
<td>48.6%</td>
<td>50.2%</td>
</tr>
</tbody>
</table>
Platooning

The same can be done if enough AVs find themselves on highways. 3 different methods show such an effect: CFD, wind tunnel, road test

Visualisation of CFD for heavy vehicles with 0° yaw headwind. Plotted are velocities, compared are two truck combinations [3]

EI: -15% UI: 0 FI: 0 [3]
Platooning

The same can be done if enough AVs find themselves on highways. 3 different methods show such an effect: CFD, wind tunnel, road test

Visualization of CFD for heavy vehicles with 0° yaw headwind. Plotted are velocities, compared are two truck combinations [3]

Model trucks in wind tunnel. Percent benefit in wind averaged drag coefficient for the entire platoon (relative to isolated vehicles without trailer boattail) as a function of vehicle spacing. Spacing between 1st and 2nd is 30’ 40’ 50’, and second and third ranges from 5’ to 220’. Higher is better [4]
Platooning

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Relative fuel saved on real track with trucks for different following distances, speeds, and gross vehicle weights. Higher is better [5]

EI: -15% UI: 0 FI: 0 [3] [4] [5]
Platooning is heavily dependent on:

- Aerodynamic shape of vehicles
- Number of vehicles
- Time in formation
- Actual formation (e.g. distance and speed between vehicles)

Estimated EI savings of 10% for light vehicles. Also possible for heavy vehicles as seen before, but no value from this study [1]
Content

- Framework to quantify effects
- Individual Effects
- Widespread adaptation
- Wider context
Virtually all vehicles on the road are AVs

We look at

- Efficient driving
- Faster travel
- Increased travel
- Specialised vehicles
- Vehicle sharing
- Electrification
Widespread adaptation

Efficient driving

Cars still drive individually efficient. However, there are enough AVs to coordinate and achieve effects such as no stops intersections.

• Fixed: traffic lights where each cycle has a fixed duration
• Fair: Slot based FIFO
• Batch: slot based with adaptive platooning converges to optimum [9]
• Fixed: traffic lights where each cycle has a fixed duration
• Fair: Slot based FIFO
• Batch: slot based with adaptive platooning converges to optimum [9]

[1] says that there’s an additional 30% EI savings
What are people doing with the time they gain?
Faster travel

Cars can drive faster and safer, but this creates more drag

\[ F_D = \frac{1}{2} \rho v^2 C_D A \]

- \( F_D \): drag force
- \( \rho \): density
- \( v^2 \): velocity
- \( C_D \): drag coefficient
- \( A \): cross sectional area
Faster travel

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[1] estimates 30% decrease in EI.

Faster and safer travel has related concepts:
- Increase in travel distance
- Lower EI by lighter cars

Widespread adaptation
Increased travel

Two concepts that will potentially increase the amount of travel:

- Consistent time in traffic
- Travel by underrepresented demographics
In [1] Schaefer et al. note:

“People are willing to spend the same amount of time in traffic”
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“People are willing to spend the same amount of time in traffic”

In addition, time spent in cars can be productive and people are willing to travel longer. This is an example of time rebound and we have a +50% UI (use intensity: VMT/vehicle) by [1]
Widespread adaptation

Increased travel: Underrepresented demographics

[14] Licensed drivers as percentage of their age group population

EI: -25% UI: 50% Fl: 0 [14]
Increased travel: Underrepresented demographics

We see that
1) Some age groups have more licensed drivers
2) There is a big difference in countries
3) There is a shift over the years

[14] Licensed drivers as percentage of their age group population
Widespread adaptation

Increased travel: Underrepresented demographics

[1] Relative travel by age

[13] Average distance driven in car per person per year in England 2018

EI: -25% UI: 50% FI: 0
Although a lot of people have license, most kilometers are driven by a narrow age group.

Average distance driven in a car or van as a passenger or driver, per person per year, in England in 2018, by gender and age (in miles).

- **EI:** -25%
- **UI:** 50%
- **FI:** 0

**[1] Relative travel by age**

**[13] Average distance driven in car per person per year in England 2018**
1/4 of US population has a disability [15]. Those are less likely to travel by car and take fewer long distance trips [1].

EI: -25%  UI: 50%  FI: 0  [1] [15]
What if the elderly, young people, and disabled people drive as much as the current 40 year olds? This results in an +40% UI increase.

Rebound effect: Easier to use -> More travel.
What if the elderly, young people, and disabled people drive as much as the current 40 year olds? This results in an +40% UI increase.

Rebound effect: Easier to use -> More travel

Indirect: What activities are those people doing, and what is their social and ecological impact?

However, those people probably won’t own a car: Related concept is vehicle sharing.
Overview of widespread adaptation so far
Specialised vehicles

Specialisation: one person car, two person cars, long distance, short distance, transportation,...
Specialised vehicles

Specialisation: one person car, two person cars, long distance, short distance, transportation,…

Relative evolution of sales-weighted average vehicle mass, engine power, engine size in the European Union [17]

Relative evolution of sales-weighted average vehicle mass, engine power, fuel economy of light duty vehicles in the US [17]
Widespread adaptation

Specialised vehicles

Specialisation: one person car, two person cars, long distance, short distance, transportation,…

Vehicles can be lighter as they are safer, and specialised for different tasks as any “driver” can now use any type of vehicle

We could get rid of e.g. [16] Airbags (up to 30kg), solid frames and crumble zones. Thus cars are not only lighter and save fuel, but require less resources to produce

-50% EI by reducing weight of 75%. Each reduction of 10% brings 6-8% EI reduction [1]
Vehicle sharing

Only at peak times, 12% of all the vehicles are on the road [1]

Private cars are used on average 50-60mins per day, the rest is spent parking somewhere [16] Can we make each car useful?

In addition, cities have therefore 15% or in extreme cases up to 33% of space dedicated to parking [16]
Vehicle sharing

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Private cars are used on average 50-60mins per day, the rest is spent parking somewhere [16] Can we make each car useful?

In addition, cities have therefore 15% or in extreme cases up to 33% of space dedicated to parking [16]

Ride sharing allows higher occupancy of cars, which gives a 12% UI reduction. More convenient than public transport as the destinations and times are flexible
Widespread adaptation

Vehicle sharing: Reduced time to market

Average age of road vehicles by country and vehicle type [18]

EI: -75% UI: 78% FI: 0 [18]
Widespread adaptation

Vehicle sharing: Reduced time to market

Average age of road vehicles by country and vehicle type [18]

Evolution of fuel consumption of new cars in the EU and USA from 1975 to 2002. Two data sets for EU. Lower is better [17]

EI: -75% UI: 78% FI: 0 [17] [18]
Widespread adaptation

Vehicle sharing: Reduced time to market

“Due to the major expense of purchasing a car, only about 7% of our vehicles are replaced in a single year [...], making improvement very gradual and incremental.” [6]
Vehicle sharing: Reduced time to market

“Due to the major expense of purchasing a car, only about 7% of our vehicles are replaced in a single year [...], making improvement very gradual and incremental.” [6]

If we reuse the same carpool, the time to market of new inventions is shorter and we can benefit faster of new inventions and more efficient vehicles
Widespread adaptation

Electrification

Issues in electric vehicles:
- Range
- Cost
Electrification

Issues in electric vehicles:
- Range
- Cost

In vehicle sharing, the cost is amortized over many people. In addition, the optimal car can be chosen, thus leading to a higher electrification rate.

Assuming that trips below 65km use electric vehicles, we get a 75% decrease in FI (fuel intensity: fuel/energy) [1]
Widespread adaptation

Recap so far

- Efficient driving: -15% EI
- Platooning: -15% EI
- Efficient driving (widespread): -30% EI
- Faster travel: +30% EI
- Increase in travel distance: +50% UI
- Increase in travel by other demographics: +40% UI
- Special vehicles: -50% EI
- Vehicle sharing: -12% UI
- Electrification: -75% FI

EI: -75% UI: 78% FI: -75%
Content

- Framework to quantify effects
- Individual Effects
- Widespread adaptation
- Wider context
Content

Gloss over relevant topics:

- Urban infrastructure
- Counter urbanization
- Freed space
- Job loss
Urban infrastructure

How does the urban infrastructure change with AV?
Urban infrastructure

AVs need less room to operate and store. For on demand fleets, we need parking and charging stations, well connected to arrive fast at a user

[19] wants separate CVs from AVs. For AVs: remove intersections and replace with merge/diverge network.

Urban infrastructure

AVs need less room to operate and store. For on demand fleets, we need parking and charging stations, well connected to arrive fast at a user

[19] wants separate CVs from AVs. For AVs: remove intersections and replace with merge/diverge network.

Remove intersections by only merging vehicles

Efficient merging design by sloped ramps in 3D
Sharing and isolation of AV and CV traffic for safety and efficiency

Underground road network. Similar to metro, but easier to maintain as it’s ”just” tunnels without additional infrastructure
More complex designs for AVs: Single vehicle exists on the left, high capacity exits on the right.
Isochrono maps of 30min reachtime in Stockholm. Left: conventional, Right: with proposed changes
Urban infrastructure

What is the cost of this additional infrastructure?
Wider context

Urban infrastructure

“Each year, more than 4 billion tonnes of cement are produced, accounting for around 8 per cent of global CO2 emissions” [20]
Wider context

Counter urbanization

People probably tend to drive longer distances. What if people move out of cities?
Counter urbanization

People probably tend to drive longer distances. What if people move out of cities?

“Sprawling requires the expansion of the road system as well as other physical infrastructures, such as water supply and waste removal—in general, sprawling tends to have negative environmental effects—increasing energy use and decreasing water and air quality” [21]
Cities are notoriously hotter than surrounding area. Can we combat those heat islands by adding trees on freed up parking space?

“What surface temperatures are higher in urban areas than in surrounding rural areas, represents one of the most significant human-induced changes to Earth’s surface climate” [23]
What to do with free space?

Cities are notoriously hotter than surrounding area. Can we combat those heat islands by adding trees on freed up parking space? If we add trees, we get additional benefits:

“
- Proximity and accessibility of greenspace affects the overall levels of physical activity
- Greenspaces reduce the heat island effect
- Being able to view greenspaces seems to have positive effects in stress reduction
“ [24]

“The [...] converge to indicate that different everyday outdoor environments can have quite different influences on stress recovery. [...] recuperation was faster and more complete when subjects were exposed to the natural settings rather than the various urban environments. “ [25]
Job losses

Number of taxis across Europe [26]

Wider context

Sweden
Population: 10.2 million
Number of taxis: 17,800
Taxi density: 1.7 per thousand residents

Finland
Population: 5.5 million
Number of taxis: 9,500
Taxi density: 1.7 per thousand residents

Norway
Population: 5.3 million
Number of taxis: 8,600
Taxi density: 1.6 per thousand residents

United Kingdom
Population: 66 million
Number of taxis: 70,900
Taxi density: 1.4 per thousand residents

The Netherlands
Population: 17 million
Number of taxis: 9,000
Taxi density: 0.5 per thousand residents

Denmark
Population: 5.7 million
Number of taxis: 4,000
Taxi density: 0.7 per thousand residents

Belgium
Population: 11.3 million
Number of taxis: 4,000
Taxi density: 0.4 per thousand residents

Germany
Population: 83 million
Number of taxis: 52,500
Taxi density: 0.6 per thousand residents

France
Population: 67 million
Number of taxis: 60,000
Taxi density: 0.9 per thousand residents
Wider context

Job losses

“Heavy truck driving is a major employment occupation in the US and Europe. In Europe around 3.2 million were employed as heavy truck drivers in 2015, which represents 1.5% of the employed population. In the US around 2.4 million people or 1.7% of the employed population are estimated to drive heavy trucks.” [27]

Number of taxis across Europe [26]
Much more...

• Additional electronics and sensors in AVs
• Additional infrastructure for redundancy and communication
• How many servers and data processing is needed for the cooperative algorithms
• If everyone can drive anywhere, how does this increase in leisure and tourism impact the environment?
• Who owns the AVs? How does this monopoly care about the environment?
• Does every social class have fair access to AVs?
Conclusion

“which will lead to a rebound effect that is difficult to estimate” [16]
Sources


- [12] https://www.immomapper.ch/de/immobilienmarkt/zurich-zh


• [29] https://en.wikipedia.org/wiki/Kaya_identity
Extra slides
Efficient driving

AVs as individual agents are not enough to achieve such *futuristic* scenarios. The vehicles have to communicate and coordinate as we assumed at the beginning. [10] worked on an algorithm for efficient intersections and simulate it for different vehicle flows and information levels.
Efficient driving

AVs as individual agents are not enough to achieve such futuristic scenarios. The vehicles have to communicate and coordinate as we assumed at the beginning. [10] worked on an algorithm for efficient intersections and simulate it for different vehicle flows and information levels.

Number of stops for different flows, demand rations, automation level, and information sharings. AVs are not enough, we need coordination to increase efficiency. Lower is better [10].
Counter urbanization

People probably tend to drive longer distances. What if people move out of cities?

Change of land due to urbanisation affects risk of flooding. Removal of soil and vegetation, filling the soil with concrete and channeling all the water into nearby rivers by drainage networks means that
1) The volume
2) The frequency
3) The peak discharge
in floods increases [22]
Counter urbanization

People probably tend to drive longer distances. What if people move out of cities?

Comparison of annual maximal discharge for two nearby rivers in the US. One is affected by urbanization, the other not [22]

Comparison of hourly discharge for two nearby rivers in the US. One is affected by urbanization, the other not [22]