Automated Driving – Evolution or Revolution?

Bart van Arem, Delft University of Technology, The Netherlands
COTA International Conference of Transportation Professionals - 7th July 2017 Shanghai
Rivium Buses (Rotterdam)

Separated track
Road based transponders
Supervisory control
Since 1999…
WePod
<table>
<thead>
<tr>
<th>Level</th>
<th>Name</th>
<th>Narrative definition</th>
<th>DDT</th>
<th>OEDR</th>
<th>DDT fallback</th>
<th>ODD</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>No Driving Automation</td>
<td>The performance by the driver of the entire DDT, even when enhanced by active safety systems.</td>
<td>Driver</td>
<td>Driver</td>
<td>Driver</td>
<td>n/a</td>
</tr>
<tr>
<td>1</td>
<td>Driver Assistance</td>
<td>The sustained and ODD-specific execution by a driving automation system of either the lateral or the longitudinal vehicle motion control subtask of the DDT (but not both simultaneously) with the expectation that the driver performs the remainder of the DDT.</td>
<td>Driver and System</td>
<td>Driver</td>
<td>Driver</td>
<td>Limited</td>
</tr>
<tr>
<td>2</td>
<td>Partial Driving Automation</td>
<td>The sustained and ODD-specific execution by a driving automation system of both the lateral and longitudinal vehicle motion control subtasks of the DDT with the expectation that the driver completes the OEDR subtask and supervises the driving automation system.</td>
<td>System</td>
<td>Driver</td>
<td>Driver</td>
<td>Limited</td>
</tr>
<tr>
<td></td>
<td><strong>ADS (“System”) performs the entire DDT (while engaged)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Conditional Driving Automation</td>
<td>The sustained and ODD-specific performance by an ADS of the entire DDT with the expectation that the DDT fallback-ready user is receptive to ADS-issued requests to intervene, as well as to DDT performance-relevant system failures in other vehicle systems, and will respond appropriately.</td>
<td>System</td>
<td>System</td>
<td>Fallback-ready user (becomes the driver during fallback)</td>
<td>Limited</td>
</tr>
<tr>
<td>4</td>
<td>High Driving Automation</td>
<td>The sustained and ODD-specific performance by an ADS of the entire DDT and DDT fallback without any expectation that a user will respond to a request to intervene.</td>
<td>System</td>
<td>System</td>
<td>System</td>
<td>Limited</td>
</tr>
<tr>
<td>5</td>
<td>Full Driving Automation</td>
<td>The sustained and unconditional (i.e., not ODD-specific) performance by an ADS of the entire DDT and DDT fallback without any expectation that a user will respond to a request to intervene.</td>
<td>System</td>
<td>System</td>
<td>System</td>
<td>Unlimited</td>
</tr>
</tbody>
</table>
Automated driving

Driver assistance/
Partial automation

Driver needs to be able to
intervene at all times

Automated parking, autocruise

Conditional/ High
automation

Vehicle in control in special
conditions

Taxibots, platooning, automated highways

Comfort, efficiency, safety, costs

Mode choice, location choice, urban
and transport planning
Many questions …

When fully automated vehicles will hit the market?

Will we travel safer?   Are we going to own or share cars?

Will we need more or less road infrastructures?

Will we still need buses?   Will there be more or less congestion?

Will we drive longer or shorter distances?

How much on-street and off-street parking spaces will still be needed?

How will cities evolve?

Will we consume more or less energy to travel?
Much progress short term and small scale impacts on driver behaviour and traffic flow.

Research on longer term, indirect, wider scale impacts on mobility, logistics, residential patterns and spatial-economic structure in its infancy.

Spatial and Transport Impacts of Automated Driving

2016-2020 M€ 2,4

www.stad.tudelft.nl
Car driving more attractive!

- **Partial automation**: Better comfort, Less accidents, Less congestion
- **High automation**: Travel time can partially be used for other purpose
- **Full automation**: Travel time can fully be used for other purposes
Value of travel time in private vehicles

The amount a traveller is willing to pay for 1 minute travel time reduction.

Trip is less useful or comfortable, traveller is willing to spend more for a shorter trip

Trip is useful and comfortable, traveller is willing to spend less for a shorter trip
Value of time in private vehicles: a stated preference experiment

Assume your next trip is from home to work, which option would you choose?

A. Conventional car
- Travel time: 15 Min
- Travel costs: € 4.50
- Walking time: 6 Min
- AV activity: driving
- Travel companions: friends and/or family

B. AV – office interior
- Travel time: 45 Min
- Travel costs: € 4.50
- Walking time: 0 Min
- AV activity: working extra time
- Travel companions: friends or family

C. AV – leisure interior
- Travel time: 30 Min
- Travel costs: € 7.50
- Walking time: 0 Min
- AV activity: do whatever you want
- Travel companions: alone

De Looff et al (2017), Value of travel time changes as a result of vehicle automation – a case study in the Netherlands (forthcoming)

242 respondents; results excluding 96 non traders

<table>
<thead>
<tr>
<th></th>
<th>Mean value of travel time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional car</td>
<td>7,91</td>
</tr>
<tr>
<td>AV Office interior</td>
<td>4,97</td>
</tr>
<tr>
<td>AV Leisure interior</td>
<td>10,47</td>
</tr>
</tbody>
</table>

- Office interior aligns with work activities
- Leisure interior does not align with work activities
- Convenience, safety and trust
Toward activity based modeling of VOTT

Input: activity wish-list, utilities, durations, time constraint

Maximisation of utility

Output: selected activities, stationary or on-board, travel mode

Compute: total time spent stationary, travelling, and obtained utility

Compare: scenarios of different travel distances, activities types, ...

<table>
<thead>
<tr>
<th>Activity</th>
<th>Utility of activity stationary</th>
<th>Duration of activity stationary (h)</th>
<th>Utility of travel time / h</th>
<th>Travel time (h)</th>
<th>Utility of activity in AV</th>
<th>Duration of activity on board (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Family dinner</td>
<td>50</td>
<td>1</td>
<td>-10</td>
<td>0.5</td>
<td>-100</td>
<td>100</td>
</tr>
<tr>
<td>Meet a friend</td>
<td>40</td>
<td>1</td>
<td>-10</td>
<td>0.5</td>
<td>-100</td>
<td>100</td>
</tr>
<tr>
<td>Repair bicycle</td>
<td>30</td>
<td>1</td>
<td>-10</td>
<td>0.5</td>
<td>-100</td>
<td>100</td>
</tr>
<tr>
<td>Watch a movie</td>
<td>20</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>10</td>
<td>1.5</td>
</tr>
<tr>
<td>Surf on internet</td>
<td>10</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>5</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Utilities, Durations, Travel Times, and Durations on Board.
- Current ACC increases congestion
- New/improved ACC start reducing congestion at 10% penetration rate
- CACC strongly reduces congestion

Note: (C)ACC modelled as ‘special’ drivers

Huisman (2016)
General findings on motorway capacity

“CACC can double roadway capacity”
- on motorways without on/off ramps -

Many microsimulations
Different reference cases
ACC and CACC
Hardly any bottlenecks

ACC changes motorway capacity between -5% and +10%
At bottlenecks change is less than +10%
Additional benefits: improving stability (CACC) and reducing capacity drop
CACC increase capacity further at penetration rates beyond 40%

Hoogendoorn et al (2014), Automated driving, traffic flow efficiency and human factors: literature review, Transportation Research Record
Network design and impacts of Automated Driving

- High automation on designated roads
- AV has 95% VOTT of regular vehicles
- Passenger Car Equivalent AV:
  - 95% penetration rate $\leq 40\%$
  - 90% penetration $>40\%$
- Automated Vehicles may travel further to be on L4 roads
- Automated Vehicles lead to shorter travel time on L4 roads

Level 4 enabled network of Delft
<table>
<thead>
<tr>
<th>Penetration Rate</th>
<th>Total Travel Cost (€)</th>
<th>Total Travel Time (h)</th>
<th>Total Travel Distance (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>71265</td>
<td>3451</td>
<td>211580</td>
</tr>
<tr>
<td>10%</td>
<td>70897</td>
<td>3448</td>
<td>211686</td>
</tr>
<tr>
<td>50%</td>
<td>67574</td>
<td>3438</td>
<td>212911</td>
</tr>
<tr>
<td>90%</td>
<td>64634</td>
<td>3429</td>
<td>213971</td>
</tr>
<tr>
<td>Max improvement</td>
<td>- 9%</td>
<td>- 1%</td>
<td>+1%</td>
</tr>
</tbody>
</table>

User equilibrium static assignment

Next steps
Dynamic assignment
Multi-user class
Optimal Network Design

A system dynamics approach

Transport system evolves over time
Demography, Economy, Transport Infrastructure, Policy, etc

Automated driving evolves over time
Technology, acceptance, regulation, incentives, impacts, …

Puylaert et al (2017), Mobility impacts of early forms of automated driving – A system dynamic approach, submitted
An abstract multi-modal transport system

Main relations

- In large cities
- Regional
- Rural
- Between large cities

Nieuwenhuijsen et al (2017)

VOT 90% rural/ regional

VOT 80% between large cities

Puylaert et al (2017), Mobility impacts of early forms of automated driving – A system dynamic approach, submitted
### Car trips increase, growth dampened by congestion

Cooperative better than autonomous, Uncertainty can be large

<table>
<thead>
<tr>
<th></th>
<th>Autonomous</th>
<th>Cooperative</th>
<th>Congestion</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>In large cities</td>
<td>+1%</td>
<td>+1%</td>
</tr>
<tr>
<td></td>
<td>Regional</td>
<td>+1%</td>
<td>+2%</td>
</tr>
<tr>
<td></td>
<td>Rural</td>
<td>+1%</td>
<td>+2%</td>
</tr>
<tr>
<td></td>
<td>Between large cities</td>
<td>+6%</td>
<td>+9%</td>
</tr>
</tbody>
</table>

**Average speed of a car trips in peak hours per relation**

1. In large cities
2. Regional
3. Rural
4. Between large cities

**Total travel time delay cars per relation**

1. In large cities
2. Regional
3. Rural
4. Between large cities
Automated Vehicles in National Market and Capacity Analysis (NMCA)

NMCA

Updated every 4 year to identify main transport problems

Used to support major transport infrastructure decisions

Typical horizon 20 years

Uses Dutch National Transport Model (LMS)

What if AVs could deliver substantial capacity improvement in 20 years?

40% of trucks capable of platooning
Platooning truck = 0.75 Normal truck

30% of passenger cars automated
Automated car = 0.70 Normal car

Value of Time
Platooning/automation -20%

<table>
<thead>
<tr>
<th>Basic (2014=100)</th>
<th>Train</th>
<th>Car driver</th>
<th>Car Passenger</th>
<th>Bus Tram Metro</th>
<th>Bicycle</th>
<th>Walking</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>2040 High</td>
<td>145</td>
<td>144</td>
<td>99</td>
<td>131</td>
<td>103</td>
<td>98</td>
<td>133</td>
</tr>
<tr>
<td>Automated driving truck platooning</td>
<td>0%</td>
<td>3%</td>
<td>1%</td>
<td>1%</td>
<td>0%</td>
<td>0%</td>
<td>3%</td>
</tr>
</tbody>
</table>

8% reduction of congestion
6% increase travel km on main roads

Other scenarios being done

I&M (2017), Gevoeligheids analyse NMCA, 14th April 2017 (in Dutch)
Snelder et al (2017) Modelling the mobility impacts of automated vehicles with strategic models: a case study with the National Model system of the Netherlands (forthcoming)
Findings

Automated vehicle impacting mobility by Value of Time and roadway capacity

System dynamics and static models show increase in trips; congestion not always resolved

Many uncertainties still exist

Challenge: integrate system dynamics with detail of static models
Fostering the promise and evolution of automated driving

- Develop efficient and reliable technology
- Collect, analyse and publish large scale real-world experience
- Study spatial, transport and societal impacts
- Regulations, type approval
- Awareness, ambitions, expectations, reality checks