Implications of Automated Driving

Bart van Arem
Who is Bart van Arem?

1982-1990: MSc (1986) and PhD (1990)
Applied Mathematics University of Twente

2003-2012 Part-time full professor University of Twente

2009-now: Delft University of Technology
• Full Professor Transport Modelling
• Chair Department Transport & Planning
• Director Transport Institute

Automated Vehicle demonstrations:
• 1998 Rijnwoude
• 2008 Eindhoven
• 2013 Amsterdam

IEEE ITS Society
• 2004-2006 EiC Newsletter
• General Chair IV 2008, Eindhoven
• General Chair ITSC 2013, The Hague
Content of this lecture

- Interest in Automated Driving
- Definitions and scenarios
- Driver behaviour
- Traffic flow behaviour
- Acceptance and deployment
- Impacts on strategic decision making
- The future of transport starts today
INTEREST IN AUTOMATED DRIVING
A first drive with fully automated vehicle...
Self driving cars can improve traffic efficiency and safety

Netherlands to facilitate large scale testing of self driving vehicles

Dutch minister of Infrastructure & Environment
Mrs Melanie Schultz
King Willem-Alexander of the Netherlands
Rijnwoude 1998

AGVs Port of Rotterdam 1993

Parkshuttle Rivium, 1999

IEEE IV 2008, Eindhoven

Grand cooperative driving challenge, Helmond 2011

Innovation relay 2013

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Beijing Jiaotong University, 9th September 2015
Dutch society and economy depend on transport

- Dense road network
- Port of Rotterdam
- High traffic volumes
- Schiphol airport
Automated vehicle field tests

Scania: truck platooning. Test on public road: 09-02-15 on the A28 Motorway at Zwolle

Province of Gelderland, TU Delft, TNO: Automated Public Transport in “Foodvalley” at Wageningen, 2016
TU Delft (Transport and Rail group): Automatic taxis as last mile transport, TU Delft Campus, 2016

TU Delft: partial automation with communication on the A10 motorway near Amsterdam, 2016

TU/e: Automated and Cooperative Renault Twizy’s, 2015
TNO/TU/e: Grand Cooperative Driving Challenge, 2016
DEFINITIONS AND SCENARIOS
<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>Fallback 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>
<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 a 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>

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Automated, autonomous, cooperative?

- **Automated**
  - Level 5: Full Automation
  - Level 4: High Automation
  - Level 3: Conditional Automation
  - Level 2: Partial Automation
  - Level 1: Drive Assistance

- **Autonomous**

- **Cooperative**

- **Manual**
Two paths for deployment

Functional
- Driver support
- Partial automation
- High/full automation
- Dedicated roads
- Mixed traffic
- Operational speed

Spatial

Full automation
- High automation

The ripple effect of automated driving

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Development of automated vehicles in the Netherlands: scenarios for 2030 and 2050

(Milakis, Schnelder, van Arem, van Wee, & Correia, 2015; work in progress)
Scenarios about development and implications of automated vehicles in the Netherlands.

**AV ...in standby**
- Fully automated & cooperative vehicles (V2V) in 2030.
- Legislation inflexibility for AV. Transport policies restraining use of AV. High regulation of AV trials.
- Modest economic growth.
- “Wait and see...” customers attitude, mid-low demand for AVs.
- No major environmental problems, but still low penetration of electric vehicles.

**High technological development**
- Fully automated & cooperative vehicles (V2V & V2I) in 2025.
- Laws allowing AV traffic. Limited regulation of AV trials.
- Public investments on AV research and on smart infrastructure.
- High economic growth.
- Positive customers attitudes, strong demand for AVs.
- Limited environmental problems. Clean technologies prevail.

**AV ...in bloom**

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**Restrictive AV policies**
- Fully automated vehicles in 2045.
- Limited legislation for AV integration. No AV trials allowed.
- Recessive economy, high unemployment.
- Negative customers attitude, almost no demand for AVs.
- Important environmental problems. Very slow transition to low-carbon economy.

**Supportive AV policies**
- Fully automated & cooperative (V2I) vehicles in 2040.
- Slow economic growth.
- “Not really interested...” customers attitude, low demand for AVs.
- Increased environmental problems. Transport sector still among major polluters.

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**AV ...in doubt**
- Low technological development

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**AV ...in demand**
Automated Vehicles will be included in Dutch environmental planning scenarios
DRIVER BEHAVIOUR
Fundamental changes in driving behaviour

Driver in control  ➔  Vehicle in control

Driver supervision

Workload, driving performance, attention, situation awareness, risk compensation, Driver Vehicle Interface, acceptance, mode transition, purchase and use
The congestion assistant

- Detects downstream congestion
- Visual and auditive warning starting at 5 km before congestion
- Active gas pedal at 1.5 km to smoothly slow down
- Takes over longitudinal driving task during congestion
Impacts on driving behaviour

Motorway scenario with congestion
Impacts on driving behaviour
Acceptance
Effects on mean speed
Effects on time headway

![Graph showing the effects on time headway with and without system.](image)

<table>
<thead>
<tr>
<th>SECTION</th>
<th>Without System</th>
<th>With System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Far before (1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Before (2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>In (3)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>After (4)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

May 31, 2006

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Potential impacts on traffic

- Solve traffic jams by increased outflow
- Prevent traffic jams by better stability
- Better distribution of traffic over network
- Decreased throughput by larger headways
- Decreased stability by lack of anticipation

Less congestion delay

Increased risk of congestion
The congestion assistant

• Detects downstream congestion
• Visual and auditive warning starting at 5 km before congestion
• Active gas pedal at 1,5 km to smoothly slow down
• Takes over longitudinal driving task during congestion
Traffic flow simulation: merging area A12 motorway, Woerden, the Netherlands

4.1 km 2.1 km
Results

Speed upstream - 10% CA

Speed upstream - 50% CA

Time (min)

Speed (km/h)

Reference
1500 m
500 m
1.0 s
0.8 s
General findings on motorway capacity

• ACC can either have a small negative or a small positive effect on capacity (~ -5% to +10%)
• Bottlenecks: increase <10%
• Positive effect stability and capacity drop
• Lower level roads?

(Shladover, Su, & Lu, 2012)

Many micro simulation studies
Difficult to compare
Focus on ACC and CACC
Hardly any bottlenecks
A20: bottleneck motorway, no more space to expand

How can AVs relieve congestion here?

3+2 cross weaving

Short on-ramp
ACCEPTANCE AND DEPLOYMENT
Acceptance

- Drivers state that they prefer warnings over control
- Control could be acceptable in special conditions such as congestion driving
- Acceptance of (different levels of) automation increases after (positive) experience
- Scepticism is declining
DEPLOYMENT RATES - EU27
BY MEMBER STATE

PS3
OBSTACLE & COLLISION WARNING

PASSENGER CARS
NEW REG. IN 2012

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Development of penetration rate

- Technological development
- Barriers
- Lifetime of cars/fleet turnover
- Costs of the cars
- Services
- Car software updates
- ...

(Litman, 2014)
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
Spatial implications

**Functional**

- Geometric redesign of roads and junctions
- Increasing sprawl residential and employment locations
- Concentration activities by better accessibility
- Redesign of urban, commercial, touristic areas
- No on street parking
- Combinations with car sharing, electric driving

**Spatial**

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IMPACTS ON STRATEGIC DECISION MAKING
Implications of Automated Vehicles for National Transport Model

Dutch National Transport Model (LMS)
- Updated every 2 year to identify main transport problems
- Used to support major transport infrastructure decisions
- Typical horizon 20 years

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

Spatial structure
Economy
Demography
Policy measures

Travel demand model

Trips (car, train, cycling, walking) ↓ Flows, travel times, congestion

Transport network, Capacities, Passenger car equivalent, Value of time

Assignment model

Iterate until equilibrium

Prediction horizon reference scenario 2030

How can this model represent the impacts of Automated Driving?

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Exploring the methodology

- Model extremely complex with many internal dependencies
- Limited ways to differentiate user and vehicle types
- Generic way of representing congestion

Parameters selected to represent the impacts of Automated Driving:
- Capacity primary road network
- Capacity secondary road network
- Passenger car equivalent factors of trucks
- Value of time
Automated Autonomous

5% capacity decrease on primary road network

<table>
<thead>
<tr>
<th></th>
<th>Index km travelled</th>
</tr>
</thead>
<tbody>
<tr>
<td>Train</td>
<td>100.3</td>
</tr>
<tr>
<td>Car driver</td>
<td>99.8</td>
</tr>
<tr>
<td>Car passenger</td>
<td>99.7</td>
</tr>
<tr>
<td>Bus, tram, metro</td>
<td>100.2</td>
</tr>
<tr>
<td>Cycling</td>
<td>100.1</td>
</tr>
<tr>
<td>Walking</td>
<td>100.1</td>
</tr>
<tr>
<td>Total</td>
<td>99.98</td>
</tr>
</tbody>
</table>

Index congestion: 115.7
Automated Cooperative

15% capacity increase on primary road network
10% capacity increase on secondary road network
10% decrease value of time commuting and business car trips

<table>
<thead>
<tr>
<th>Mode</th>
<th>Index km travelled</th>
</tr>
</thead>
<tbody>
<tr>
<td>Train</td>
<td>98.8</td>
</tr>
<tr>
<td>Car driver</td>
<td>100.8</td>
</tr>
<tr>
<td>Car passenger</td>
<td>101.4</td>
</tr>
<tr>
<td>Bus, tram, metro</td>
<td>99.2</td>
</tr>
<tr>
<td>Cycling</td>
<td>99.3</td>
</tr>
<tr>
<td>Walking</td>
<td>99.4</td>
</tr>
<tr>
<td>Total</td>
<td>100.10</td>
</tr>
</tbody>
</table>

Index congestion: 69.1

4-8% VMT increase (Gucwa, 2014)

100% capacity increase
Car trips valued as high quality rail
Findings

• Overall impacts credible but small
• Crude assumptions made for capacities
• Impacts on travel demand small (only modelled indirectly)

Further research planned
• Capacity estimation
• Impacts on travel demand

Automated driving will be included in 2017 update of the National Transport Model
THE FUTURE OF TRANSPORT STARTS TODAY…
High Expectations

- Efficient travel
- Safety
- Comfort, quality of life
- Energy, emissions
- Economy

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Huge investments in technology

Sensing
Communication
Positioning
Data fusion
Situation awareness
Trajectory predication
Cooperative control
Traffic management
Driver monitoring

Performance
Complexity
Security
Privacy
Liability
Failure modes
Weather conditions
Energy
Cost
Many uncertainties about implications

- Driving behaviour, traffic flows, travel behaviour
- Infrastructure land spatial impacts
- Societal implications

Current and future pilots will enable to study these impacts in a more realistic way than ever!
The road to 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
Thank you!

Cars automatic in 20 years

Tell it we don’t appreciate these types of jokes and to come back right away