How traffic flow simulation can teach automated driving

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The world is changing....

2005

2013

Luca Bruno /AP

Michael Sohn /AP
Mobility Buzz Words

Demographic change & urbanization

Electrification → Decarbonization

Sharing mobility → MaaS

Assisted → Autonomous → Connected
Car commercials

Mercedes: https://theadsgarage.com/tag/commercial/page/2/
BMW: http://dirs-n-dops.de/manual-wenger.html
Ford: https://www.ford.com/finance/commercial-financing
.. and reality
Expectations of Connected & Automated Vehicles (CAV´s)

**Efficiency**
- capacity increase on motorways, shorter headways
- higher saturation flow at signals
- Friedrich, B; Wagner, P;...

**Environment**
- less vehicles (MaaS)
- efficient driving

**Safety**
- lower risk
- 90% accid. human related
Capacity

Conventional cars
- human behavior
- unequal headways
- heterogeneous traffic flow

Automated cars
- equal headways
- shorter latency (V2V)
- homogenous traffic flow
- higher density?
- higher speed?
- higher capacity?
- increased stability?
- higher throughput?

Source: Neuhold, Fellendorf: MobilTUM, 2015
capacity: simple calculation

Vehicles need space: \( L = vT + \ell_{\text{car}} \)
- \( v \) velocity, \( T \) headway, \( \ell_{\text{car}} \) vehicle length
- Thus: \( \frac{1000}{L} = \frac{1000}{vT+\ell_{\text{car}}} =: k \) vehicles per kilometer per lane
- Flow \( q = k \, v \), with \( q = \frac{1000 \, v}{vT+\ell_{\text{car}}} \)

Some values:
- \( \ell_{\text{car}} = 6m, T = 1.8 \, s, v = 22m/s (\approx 80 \, \text{km/h}) \)
- \( k = 20 \, \text{veh/km} \) and \( Q = \max\{q_i\} = 1740 \, \text{veh/h} \)

and automated
- \( T = 0.5s \rightarrow k = 87 \, \text{veh/km} \) and \( Q = 6886 \, \text{veh/h} \)
- \( T = 0 \quad \rightarrow k = 133 \, \text{veh/km} \) and \( Q = 13200 \, \text{veh/h} \)
BUT simplification does not meet reality

single lane
  - car following model
  - longitudinal movement in Vissim

multilane infrastructure
  - motorways (eg. merge/diverge)
  - urban arterials (eg. intersections)
  - longitudinal and lateral movement

Adaptive Cruise Control (ACC)
  - car following

Advanced driver-assistance Systems (ADAS)
  - car following
  - including lane change
Capacity studies on ADAS and CAV´s among others:

FAT 296
- TU Munich and KIT: Capacity impact of partial and highly automated driving,
- Study for the German Automobile Association (2014-2016)
- Vissim with adjusted longitudinal and lateral parameter values

Motamedidehkordi, N.; Margreiter, M., Benz, Th: Effects of Connected Highly Automated Vehicles on the Propagation of Congested Patterns on Freeways, TRB 16-1802

https://www.vda.de/de/services/Publikationen/fat-schriftenreihe-296.html
CAV´s modelled by parameter changes

<table>
<thead>
<tr>
<th>Name des Parameters</th>
<th>Erläuterung</th>
<th>Einheit</th>
<th>Normalfahrer</th>
<th>HAF</th>
<th>Kommunizierende HAF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grundverhalten</td>
<td></td>
<td></td>
<td>Rechtsfahrgebot</td>
<td>Rechtsfahrgebot</td>
<td>Rechtsfahrgebot</td>
</tr>
<tr>
<td>Maximale Verzögerung (Eigene)</td>
<td>Maximale Verzögerung für Fahrstreifenwechsel aufgrund der vorgegebenen Routen für das eigene überholende Fahrzeug</td>
<td>m/s²</td>
<td>-4.00</td>
<td>-4.00</td>
<td>-4.00</td>
</tr>
<tr>
<td>Maximale Verzögerung (Folgefahrzeug)</td>
<td>Obergrenzen der Verzögerung für das Folgefahrzeug bei einem Fahrstreifenwechsel</td>
<td>m/s²</td>
<td>-3.00</td>
<td>-2.50</td>
<td>-3.00</td>
</tr>
<tr>
<td>Akzeptierte Verzögerung (Eigene)</td>
<td>Untergrenzen der Verzögerung für das eigene Fahrzeug für einen Fahrstreifenwechsel</td>
<td>m/s²</td>
<td>-1.00</td>
<td>-1.00</td>
<td>-1.00</td>
</tr>
<tr>
<td>Akzeptierte Verzögerung (Folgefahrzeug)</td>
<td>Untergrenzen der Verzögerung für das Folgefahrzeug bei einem Fahrstreifenwechsel</td>
<td>m/s²</td>
<td>-0.75 (Lkw: -0.50)</td>
<td>-0.75 (Lkw: -0.50)</td>
<td>-0.75 (Lkw: -0.50)</td>
</tr>
<tr>
<td>Minimum Nettoweglücke (vorne/hinten)</td>
<td>Mindestabstand, der nach einem Fahrstreifenwechsel zwischen zwei Fahrzeugen mindestens vorhanden sein muss</td>
<td>m</td>
<td>0.50</td>
<td>1.00</td>
<td>' 0.50</td>
</tr>
<tr>
<td>Auf langsameren Fahrstreifen wenn Kollisionszeit mind. s</td>
<td>Mindestabstand in Sekunden, der zu einem Vordermann auf dem langsameren Fahrstreifen vorhanden sein muss, damit ein überholendes Fahrzeug auf den langsameren Fahrstreifen wechselt.</td>
<td>s</td>
<td>11 (Lkw: 1)</td>
<td>8 (Lkw: 1)</td>
<td>8 (Lkw: 1)</td>
</tr>
</tbody>
</table>

^FAT 296, 2017, S 19
Capacity studies on ADAS and CAV´s among others:

**FAT 296**
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**VEGAS**
- TU Graz and Virtual Vehicle (2016-2017); same topic
- supported by bmvit and Asfinag
- Vissim with driver.dll and driving simulator

Haberl, Neuhold, Fellendorf, Rudieger, Kerschbauer, Eichberger, Rogic: Simulation assisted impact analyses of automated driving on motorways for different Levels of automation and penetration, mobil.TUM 2017, to be published
Objective:
- impact of automated driving (AD) on availability of the Austrian motorway network

Methodology
VEGAS: general approach

**Changes of Capacity due Automated Driving via Microscopic Simulations**

**Automated Driving Functions** via MATLAB/Simulink

Changes of Capacity due Automated Driving

Projection of Changed Capacity to the Network $\Delta C$

8 Typical Link Segments

<table>
<thead>
<tr>
<th>2+1 lanes change</th>
<th>3+1 lanes change</th>
<th>3+1 lanes diverge</th>
<th>3+1 lanes diverge</th>
</tr>
</thead>
<tbody>
<tr>
<td>~83%</td>
<td>~83%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Driving Simulator Study

Haberl, Rudieger et al. mobil.TUM 2017, to be published
Driver.DLL functions

- Init DriverDLL
- Set Data
  - VISSIM provides
    - EGO-vehicle (pos, v, type, ..)
    - neighboring vehicles (pos, v, type, ..)
    - network topology (static)
    - infrastructure control (dynamic)
- Get Data
  - VISSIM receives EGO vehicle
    - target acceleration
    - Lane data (change active, target lane, angle)
- Kill DriverDLL
AD in driver.DLL and state machine for lateral movement

Haberl, Rudieger et al. mobil.TUM 2017, to be published
Automatic Driving Function as driver.dll

Traffic Jam Assist – Level 2
- at congestion up to 30 km/h with advanced ACC + Stop & Go
- target headway as parameter (0.5s; 0.9s; 1.1s; 1.8 s)

Traffic Jam Chauffeur – Level 3
- at dense traffic up to 60 km/h with advanced ACC + Stop & Go
- target headway as parameter (0.5s; 0.9s; 1.1s; 1.8 s)

Haberl, Rudieger et al. mobil.TUM 2017, to be published
Automatic Driving Function as driver.dll (cont’d)

Highway Pilot – Level 4
- automated driving on motorways and multilane highways up to 130 km/h
- no ad-hoc platooning as no industry-standard

Truck Platooning – Level 3
- platooning at rightmost lane
- no special handling of trucks leaving platoon

Haberl, Rudieger et al. mobil.TUM 2017, to be published
### Automated Driving Functions (ADF) for SAE2, SAE3 and SAE4

- Model specific ADF for microscopic traffic flow simulation (VISSIM)

<table>
<thead>
<tr>
<th>Modelled ADF</th>
<th>Longitudinal control</th>
<th>Lateral control</th>
<th>V2V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traffic Jam Assist – SAE Level 2</td>
<td>VISSIM + Driver-DLL &lt;30km/h</td>
<td>VISSIM + Driver-DLL &lt;30km/h (no lane-change)</td>
<td>No</td>
</tr>
<tr>
<td>Traffic Jam Chauffeur – SAE Level 3</td>
<td>VISSIM + Driver-DLL &lt;60km/h</td>
<td>VISSIM + Driver-DLL &lt;60km/h (no lane-change)</td>
<td>No</td>
</tr>
<tr>
<td>Highway Chauffeur – SAE Level 3</td>
<td>Driver-DLL: PC 130km/h, HGV 90km/h</td>
<td>Driver-DLL</td>
<td>No</td>
</tr>
<tr>
<td>Highway Pilot – SAE Level 4</td>
<td>Driver-DLL: PC 130km/h, HGV 90km/h</td>
<td>Driver-DLL</td>
<td>Yes</td>
</tr>
<tr>
<td>C-ACC Platooning of HGV – SAE Level 1</td>
<td>Driver-DLL</td>
<td>VISSIM Driver</td>
<td>Yes</td>
</tr>
<tr>
<td>Truck Platooning – SAE Level 3</td>
<td>Driver-DLL</td>
<td>Driver-DLL</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Haberl, Rudieger et al. mobil.TUM 2017, to be published
Testing typical motorway network elements

- Guideline specific elements (RVS 03.05.13) for merge (M), exit (E) and weaving (W)

<table>
<thead>
<tr>
<th>2+1RM</th>
<th>3+1RM</th>
<th>2-1RE</th>
<th>3-1RE</th>
<th>2-lane</th>
<th>3-lane</th>
<th>2+1VV</th>
<th>3-1 sub</th>
<th>2+1 add</th>
</tr>
</thead>
</table>
Driving Simulator Study

Objective:
- drivers’ acceptance of AV
- Calibrate Vissim parameters

Test site
- 3-lane motorway section of ~12 km with 5 entries
- Vehicle demand 60% of guideline capacity, 23% of vehicles exit/enter at junction
- 10% heavy good vehicles (HGV)

3 Scenarios per person
- Simulator vehicle runs as SAE 0
- SAE 0
- SAE 4: short headway 0.9 sec
- SAE 4: long headway 1.8 sec

Off-ramp in VISSIM
A1, B1, C1

On-ramp in VISSIM
A2, B2, C2

Weaving section in VISSIM
D, E

Haberl, Rudieger et al. mobil.TUM 2017, to be published
Driving Simulator at TU Graz, Institute of Automotive Engineering

CUEING (HARDWARE)
- VISUAL CUEING
- ACOUSTIC CUEING
- HAPTIC CUEING
- MOTION CUEING

REAL-TIME SIMULATION FRAMEWORK

SIMULATION (SOFTWARE)
- EGO VEHICLE DYNAMICS
- ADAS SENSOR MODELS
- ADAS DRIVING FUNCTIONS
- TRAFFIC SIMULATION

PTWinSim Podium Technology
- Real-time communication of each single module
- Manage start & end of simulation

PTV VISSIM DS Interface
- Operate several external vehicles
- Provide positions of simulation vehicles for DS

Physiological Measurements

Traffic Simulation Interface
- Data preparation for application in the Driving Simulator
- Interpolation of VISSIM 20 Hz to DS 200 Hz

© Eichberger et al. (2017)
Test Drivers’ Acceptance of Automated Vehicles

some flaws with Driver.DLL – vehicles

- excessive lane changes
- runs over shoulder
Driving Simulator – different scenarios
5 features tested in simulation scenarios

1. feature (n=8)  
   Link Segments

2. feature (n=6)  
   Penetration Rates

3. feature (n=3)  
   Speed

4. feature (n=3)  
   HGV Ratios

5. feature (n=3)  
   Vehicle Input Ratios

<table>
<thead>
<tr>
<th>Vehicle input ratio</th>
<th>Mainline</th>
<th>Ramp</th>
</tr>
</thead>
<tbody>
<tr>
<td>GT-2</td>
<td>64%</td>
<td>36%</td>
</tr>
<tr>
<td>GT-3-4</td>
<td>80%</td>
<td>20%</td>
</tr>
<tr>
<td>GT-5-6</td>
<td>91%</td>
<td>9%</td>
</tr>
</tbody>
</table>

Haberl, Neuhold, et al. mobil.TUM 2017, to be published
Results of Typical Motorway Segments – 2+1 Lanes: SAE0

DCP = Data Collection Point

Haberl, Neuhold, et al. mobil.TUM 2017, to be published
Results of Typical Motorway Segments – 2+1 Lanes: SAE0

- 5% SV, v80: No Results
- 10% SV, v80: No Results
- 15% SV, v80: No Results
- 5% SV, v100: No Results
- 10% SV, v100: No Results
- 15% SV, v100: No Results
- 5% SV, v130: No Results
- 10% SV, v130: No Results
- 15% SV, v130: No Results

Haberl, Neuhold, et al. mobil.TUM 2017, to be published
Results of Typical Motorway Segments – 2+1 Lanes: SAE4 - 0.9 seconds

DCP = Data Collection Point

DCP 1  DCP 2  DCP 3  DCP 4

5000m  300m  1200m

No Result!

+7.3% capacity of SAE0

+7.8% capacity of SAE0

+16.1% capacity of SAE0

Haberl, Neuhold, et al. mobil.TUM 2017, to be published
Results of Typical Motorway Segments – 2+1 Lanes: SAE4 - 1.8 seconds

Haberl, Neuhold, et al. mobil.TUM 2017, to be published
Capacity Assessment via Speed-Flow-Diagrams without Breakdowns

1. Values considered: no increase in traffic volume over several time intervals
2. Determination of the 90th percentile of the values
3. Find the value corresponding to or closest to the 90th percentile

Haberl, Neuhold, et al. mobil.TUM 2017, to be published
Results of Typical Motorway Segments – 2+1 Lanes

Haberl, Neuhold, et al. mobil.TUM 2017, to be published
Conclusions of VEGAS

Summary

- Similar acceptance of automated vehicles with headway of 0.9 or 1.8 sec
- Capacity increase depends on position of data collection point
- Performance analysis on entire motorway network (upcoming)

Methodological shortcomings

- **Modeling of AD vehicles by driver.DLL to be improved**
- unnecessary lane changes
- difficulties in lane keeping
- platooning to be developed

<table>
<thead>
<tr>
<th>LOS A</th>
<th>LOS B</th>
<th>LOS C</th>
<th>LOS D</th>
<th>LOS E</th>
<th>LOS F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume/Capacity</td>
<td>≤ 0,30</td>
<td>≤ 0,55</td>
<td>≤ 0,75</td>
<td>≤ 0,90</td>
<td>≤ 1,00</td>
</tr>
<tr>
<td>Street segments</td>
<td>4 147</td>
<td>5 749</td>
<td>3 066</td>
<td>1 105</td>
<td>541</td>
</tr>
<tr>
<td>Ratio of LOS</td>
<td>26.0%</td>
<td>36.1%</td>
<td>19.2%</td>
<td>6.9%</td>
<td>3.4%</td>
</tr>
</tbody>
</table>
Lateral movement

Vissim contains years of experience in modeling lateral movement

1. DVU’s (driver-vehicle-units) push harder to neighboring lane as lane drop appears
2. Rear vehicles may open up gap
3. DVU’s may accelerate above desired speed
4. DVU’s do path planning by reverse routing tree
Example path planning in microsimulation

- Vissim network topology supports variety of infrastructure setups
  - parallel links no lane change
  - single multi-lane links lane change
Path planning, urban arterial

- quick merge at both main lanes without usage of left turn bay
- similar to mainline direction (moderate acceleration)
- similar headway to lead and lag vehicle
Path planning, urban arterial

- midpoint lane change crossing both lanes
  a) accelerate quickly to cut rear vehicle
  b) accelerate moderately to change behind rear veh.
Path planning, urban arterial

- midpoint lane change crossing both lanes
  a) accelerate quickly to cut rear vehicle
  b) accelerate moderately to change behind rear veh.
lateral movement lane-by-lane

a) moderate acceleration to change prior to lag vehicle
b) moderate deceleration to change behind lag vehicle
Delft integrated Traffic & Travel Laboratory comprises several research projects (model applications and model development)

Urban Mobility Lab with multimodal real-time modeling of Amsterdam region

Open Traffic Simulation (OTS)

Many of the commercial software packages available have their origins in the academic world, but are now developed and distributed by specialized software companies. In an ideal world academia and practice collaborate continuously along the lines sketched in Figure 1. In the real world, however, there is much fewer interaction between academia and practice once simulation software is commercialized. Particularly microscopic traffic simulation packages are black boxes, in which it is impossible to unravel which underlying mathematical and numerical choices have been made, and what the consequences of these are in terms of model validity. This black-box problem essentially forces most academic researchers to reinvent the wheel and to code an entire simulation model from scratch, even in case the research objective is to develop a very specific innovation (e.g. a new car following model).
human factors (HF) in traffic flow simulation

- Car-following model: Human Driver Model (HDM) based on the former Intelligent Driver Model (IDM) by Treiber et al. and implemented in OpenTrafficSim (OTS)

- idea HDM: drivers have slow reaction time but anticipate future traffic states

\[
a(t) = a_{\text{max}} \cdot \min \left( \max \left( 1 - \left( \frac{v(t)}{v_0} \right)^4, \frac{-b_0}{a_{\text{max}}}, 1 - \left( \frac{s^*(t)}{s(t)} \right)^2 \right) \right)
\]

\[
s^*(t) = s_0 + v(t) \cdot T + \frac{v(t) \cdot \Delta v}{2 \sqrt{a_{\text{max}} \cdot b}}
\]

- idea OTS: if drivers get distracted, desired speed drops and reaction time increases


Example Human Factors

- at large reaction times deteriorates safety (collisions and time-to-collision (TTC))

incident on opposite link leads to max distraction at x2 keeping until x3 with gradual increase from x1

- predicting effects on efficiency and safety of vehicle automation

Van Lint, et al., TRB (16-2917)
MAVEN - Managing automated vehicle at signalized intersections

- Road infrastructure will monitor and support vehicles movements at signalized intersections
- Beyond ADAS and C-ITS with signal plan negotiation for adaptive traffic signal control
- develop suitable communication protocols, test via simulation and a real-world prototype
  (main contributions by MAP (NL), DLR, Hyundai, TomTom and city councils)
- particular infra-assisted signal control measures:
  - phase negotiation (signal timing vs. arrival pattern), speed advisory, lane advisory
  - Platoon management: forming, joining, progression, leaving platoons
  - Conventional traffic and vulnerable road users

MAVEN is funded by the EC Horizon 2020 Programme under Grant No 690727, 09/2016-08/2019
MAVEN – system concept
concluding remarks

1. (Mobility-) times are changing rapidly;
   Connected & Automated Vehicles require numerical modeling

2. Microscopic traffic flow simulators within co-simulation environments

3. Software tools without programming interfaces not being applied in R&D

4. VISSIM (and others) have hidden mathematical models
   which could be useful for CAV-development
concluding remarks

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2. Microscopic traffic flow simulators within co-simulation environments
3. Software tools without programming interfaces not being applied in R&D
4. VISSIM (and others) have hidden mathematical models which could be useful for CAV-development

Thank for your attention
martin.fellendorf@tugraz.at