Needs for Physical Models and Related Methods for Development of Automated Road Vehicles

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## Automated Driving

**SAE J3016**

### Reference:
- [Matthijs Klomp, et al, 2019](#)
- [SAE, 2014](#)

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**Figure 1:** Driverless concepts: Volvo Vera (a) and 360c Concept (b) [Volvo Trucks and Volvo Car Group, respectively](#)

**Figure 2:** Volvo external steering [22] [Matthijs Klomp, et al, 2019](#)

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

<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 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 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 must 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>
“Function Architecture” for vehicle motion & energy

Vehicle Environment

Traffic Situation Management
- Traffic Situation
- Traffic Situation Management

Vehicle Motion Management
- Vehicle Motion
- Accelerations
- Velocities
- Wheel torques, axle steering angles

Motion Support Device Management

Route Management
- Route
- Route Management

Human Machine Interface
- Human Machine Interface
- Requests, Estimates, Confidence

Reference: [Nilsson, 2017]
Models for vehicle motion and energy control design

- **Route Management**
- **Traffic Situation Management**
- **Vehicle Motion Management**
- **Motion Support Device Management**

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**Human Machine Interface**

- **physical models**
  - velocity & energy
  - motion relative
  - lane & traffic
  - motion & individual
tyre forces

- **Data-driven models**
  - macro traffic
  - drivers
  - micro traffic
  - estimators

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**Sub-system/actuator models**

- wheelHub
- motor
- brake
- sensor
Vehicle Environment

Route Management

Traffic Situation Management

Vehicle Motion Management

Motion Support Device Management

Human Machine Interface

Next speakers

- Peter
- Mats
- Bengt
Traffic Situation Management,
Dynamically Feasible Trajectories,
Peter Nilsson, Volvo Trucks
Examples of challenges for TSM

**Behaviour planning (Tactical decision)**
- Predictions of surrounding traffic and VRUs
- Sensor imperfections and occlusions
- Consistent and predictable behaviour
- Computational efficient methods

**Motion Planning (Trajectory planning)**
- Predictions of surrounding traffic and VRUs
- Collision free trajectories
- Comfortable and predictable trajectories
- Dynamically feasible trajectories

**Vehicle Longitudinal and Lateral Control**
- Robust control
- Transitions between driving modes
- Thrust and comfort

**Functional safety**

**Examples of challenges for TSM**

- Robust control
- Thrust and comfort
- Transitions between driving modes
Trajectory planning

“Trajectory planning is a generalization of path planning, involved with planning the state evolution in time while satisfying given constraints on the states and actuation”

Commonly used methods:

• Numerical optimization (e.g. MPC)
• Graph search (e.g. A*)
• Neural network (e.g. Nvidia PilotNet)
• ...

Trajectory planning example: left curve, tractor semi-trailer
Heavy duty combination vehicles

Example of motion constraints:

- Position of first unit
- Position of trailer units (off-tracking)
- Roll-over threshold (rearward amplification)
- ...
Trajectory planning modelling

Example of modelling:

• One-track models: $\dot{x} = f(x, u, w)$
• Possible states for A-double
  • 1st unit (tractor): $v_x, v_y, \dot{\psi}_1$
  • 2nd unit (trailer): $\Delta \psi_1, \Delta \dot{\psi}_1$
  • 3rd unit (dolly): $\Delta \psi_2, \Delta \dot{\psi}_2$
  • 4th unit (trailer): $\Delta \psi_3, \Delta \dot{\psi}_3$
Vehicle variants and trajectory planning challenges

Vehicle variant combinatorics:

- Powertrain: $\approx 10^2$ variants
- Chassis: $\approx 10^3$ variants
- Vehicle load: $\approx 7 - 120t$ (incl. different heights to CoG)
- Vehicle units: 1-4

Challenge:

Trajectory planning methodology needs to scalable and robust with respect to variant combinatorics

Trajectory planning example: Roundabout, tractor semi-trailer
Vehicle Motion Management,
Road friction estimation,
Mats Jonasson
Challenges for VMM

Reference: [Matthijs Klomp, et al, 2019]
Road condition – road friction

More than 10% of all accidents occur because of slippery conditions*

In the US: yearly approx 500 000 accidents of which 1800 are deadly*

ABS activation, friction can be found $\mu \approx \frac{f}{f_z}$

Definitions:
- Low friction $0 < \mu \leq 0.4$
- Mid friction $0.4 < \mu \leq 0.7$
- High friction $0.7 < \mu$

To estimate friction the tyre must at least be excited to the nonlinear region at “the bend”

Most driving take place here, not possible to distinguish between low or high friction

* Reference: [IVSS Road Friction Estimation Part II]
* Reference: [US Department of Transportation – Federal Highway Administration]
** Reference: [Wallman. Tema vintermodell – olycksrisker vid olika vinterväglag]
Confusion matrix of road friction

- **Low (snow)**:
  - Vehicle speed can be adapted to friction

- **High (dry asphalt)**:
  - False slippery warnings
  - AD Vehicle will drive unacceptably slow (not transport efficient)

- **False slippery warnings**:
  - AD Vehicle will drive too fast (not safe)
  - High frequency of accidents

Reference: [Matthijs Klomp, et al, 2019]
Methods for road friction estimation

Optical measurement device
- Contactless
- Requires a map from texture to friction

Model-based estimator
- Use the tyre as the sensor
- Requires knowledge about tyre physics

Machine learning estimator
- Use features without knowledge of physics
- Requires training
State-of-the-art model-based estimator

Pre-processing
Wheel speeds, Inertial Meas. Syst. Steering angle

Kinetic and kinematic models

Tyre forces
Tyre slip

Friction estimator

\( \hat{\mu} \)

Graph showing normalized traction force vs. slip.
Features and correlation to friction

Features 1...86

Temperature, GPS, vehicle speed, surface and road type are important features for friction estimation.

Surface & road type are not available in the sensor suite -> important to use a new sensor e.g. a camera.

Temperature, GPS, vehicle speed, surface and road type are important features for friction estimation.

* Reference [Roychowdhury, et al, 2018]
Challenges road friction estimation

• General:
  • Difficult to identify friction for normal driving (low friction utilization)

• Model-based:
  • Model uncertainties for different tyres - the physics is hard to model
  • The pre-processing is not accurate enough

• Machine learning:
  • Generalizability of machine learning algorithms to various situations
  • Generalizability would require large testing
  • Training of machine learning algorithms require ground truth – road friction is hard to measure

Reference [Jonasson, et al] 2018
Motion Devices,
Virtual Verification, Wheel Model,
Bengt Jacobson
Models for Virtual Verification:

- Higher **accurate** and larger **validity** range than for control design.
- But **only simulate-able**, no need for linearized, inversion, etc.
...one view of model based engineering

**Real world**

- Physical modelling
- Explicit form modelling
- Mathematical modelling

**Theoretical world**

- Computational/Simulation
- Interpret results, judge model validity

- Formulate engineering task (problem)
- Initial Design
- Re-Design
- Evaluate requirement fulfilment
- Final Design

**Real-world testing**

- OK
- NOK

≈ ODE
≈ DAE (Modelica)
≈ Drawing

**Virtual Verification**
Wheel model as example

104 tonnes, 33 m

\[(1 + 3 + 4 + 2 + 3) \cdot 2 = 26 \text{ wheels}\]
Wheel model use cases

Control Longitudinal **vehicle** translation

Control Longitudinal **wheel** rotation

\[ T_p + T_b \]

\[ \omega \]

\[ v_x, v_y \]

\[ F_x, F_y, F_z \]

\[ T_{ibCReq} \]

\[ S_{ixAbsMaxReq} \]

\[ T_{ipActl}, v_{ixwActl}, \omega_{iSampled} \]

**Brake Actuator and Actuator Control**

\[ t_{delay}, t_{sample} \]

**Mechatronic Wheel**

\[ (F_{ibPist} \propto T_{ibC}) \]

**Mechanical Wheel**

\[ R, J_w \]

**Tyre parameters**

\[ F_{ixw}, F_{iyw} \]

\[ F_{iz}, T_{ip} \]

\[ F_{izw}, F_{lyw} \]
Wheel model, Mechanical challenges

Continuously Renewed Friction Surfaces

Relative Velocity Direction

Dry Friction in Brake

Rolling Resistance

Multiple wheels

If vehicle standstill and two or more wheels locked: Statically underdetermined

\[ F_x = C_x \cdot s_x; \]
\[ s_x = \frac{R \cdot \omega - v_x}{|R \cdot \omega|}; \]

\[ J \cdot \dot{\omega} = T - F_x \cdot R - T_R; \]
\[ T_R = - \text{sign}(\omega) \cdot (T_{bc} + RRC \cdot R \cdot F_z); \]

\[ [F_x, F_y] = \min(C_{xy} \cdot s_{xy}, \mu \cdot F_z) \cdot [\sin(\theta_{Fxy}), -\cos(\theta_{Fxy})]; \]
\[ s_{xy} = \frac{(R \cdot \omega - v_x)^2 + v_y^2}{|R \cdot \omega|}; \]
\[ \theta_{Fxy} = \arctan2(-v_y, (R_w \cdot \omega - v_x)); \]
Wheel model in its model context

Vehicle Motion Management
Motion Support Device Management
Vehicle Environment
Traffic Situation Management, TSM
Vehicle Motion Management, VMM
Human Machine Interface

Mechatronic Wheel
Brake Actuator with Actuator Control
Mechanical Wheel
Suspension and Vehicle Body
Vehicle Environment

Mechatronic Actuator
Mechatronic Sensor
Environment (other vehicles, lane edges, …)

Propulsion Actuator with Actuator Control

Physical quantity
Signal
Conclusions
Automated driving needs modelling in many aspects:

- TSM and VMM needs Physical modelling for “Control/algorithm design”.
- “Virtual verification” drives Physical modelling, incl. exchange of models between organisation.
References


IVSS Road Friction Estimation Part II Report, http://www.ivss.se

US Department of Transportation – Federal Highway Administration


Thanks for your attention