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

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Automated Driving

SAE J3016

<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>Failback 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 accelerating, and deceleration using information about the driving environment with the expectation that the human driver will 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 accelerating, and deceleration using information about the driving environment with the expectation that the human driver will 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>

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

Figure 2: Volvo external steering [22]

Reference: [Matthijs Klomp, et al, 2019]

Reference: [SAE, 2014]
“Function Architecture” for vehicle motion & energy

Vehicle Motion Management

Traffic Situation Management

Vehicle Environment

Motion Support Device Management

Route Management

Status, Capabilities, Requests

Estimates, Confidence

velocities

accelerations

wheel torques, axle steering angles

requests from human driver devices

Environment observations

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

- **Vehicle Environment**
- **Route Management**
- **Traffic Situation Management**
- **Vehicle Motion Management**
- **Motion Support Device Management**
- **Human Machine Interface**

**Physical Models**
- velocity & energy
  - fuel / SOC
- motion relative lane & traffic
- motion & individual tyre forces

**Data-Driven Models**
- macro traffic
- drivers
- micro traffic
- estimators

**Sub-system/Actuator Models**
- wheelHub
- cam
- brake
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)**
- Situation assessment
- Predictions of surrounding traffic and VRUs
- Consistent and predictable behaviour
- Sensor imperfections and occlusions
- 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**
- Thrust and comfort
- Robust control
- Transitions between driving modes

**Functional safety**
- Candidate manoeuvres
- Exit ramp
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
Example of motion constraints:

- Position of first unit
- Position of trailer units (off-tracking)
- Roll-over threshold (rearward amplification)
- ...
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: \( \approx 7 - 120 \) t (incl. different heights to CoG)
- Vehicle units: 1-4

Challenge:

Trajectory planning methodology needs to be 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*

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”

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

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)

- **Assumed friction**
  - AD Vehicle will drive too fast (not safe)
  - High frequency of accidents

- **True friction**
  - Vehicle speed can be adapted to friction

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

\[ \tilde{\mu} \]

Wheel speeds, Inertial Meas. Syst. Steering angle

Pre-processing

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Friction estimator

\[ \tilde{\mu} \]
Features and correlation to friction

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
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

Theoretical world

Explicit form modelling

Mathematical modelling

Physical modelling

Approximates:

- Explicit form modelling $\approx$ ODE
- Mathematical modelling $\approx$ DAE (Modelica)
- Physical modelling $\approx$ Drawing

Formulate engineering task (problem)

Initial Design

Re-Design

Evaluate requirement fulfilment

OK

Final Design

NOK

Real-world testing

Interpret results, judge model validity

$\approx$ Virtual Verification

Evaluation

$\approx$ Drawing
Wheel model as example

104 tonnes, 33 m

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

Control Longitudinal **vehicle** translation

Control Longitudinal **wheel** rotation
Wheel model, Mechanical challenges

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

\[ s_{xy} = \sqrt{\frac{(R \cdot \omega - v_x)^2 + v_y^2}{|R \cdot \omega|}}; \quad \theta_{Fxy} = \arctan2(-v_y, R_w \cdot \omega - v_x); \]

\[ F_x, F_y = \min(C_{xy} \cdot s_{xy}, \mu \cdot F_z) \cdot [\sin(\theta_{Fxy}), -\cos(\theta_{Fxy})]; \]

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

If vehicle standstill and two or more wheels locked: Statically underdetermined
Wheel model in its model context

Vehicle Motion Management
Motion Support Device Management
Vehicle Environment
Traffic Situation Management, TSM
Vehicle Motion Management, VMM
Mechatronic Wheel
Brake Actuator with Actuator Control
Mechanical Wheel
Suspension and Vehicle Body
Vehicle Environment
Conclusions
Automated driving needs modelling in many aspects:

• TSM and VMM needs Physical modelling for “Control/algorithmdesign”.

• “Virtual verification” drives Physical modelling, incl. exchange of models between organisation.
References


SAE, *Taxonomy and Definitions for Terms Related to On-Road Motor Vehicle Automated Driving Systems*, Standard J3016, 2014. [https://saemobilus.sae.org/content/j3016_201401](https://saemobilus.sae.org/content/j3016_201401)

IVSS Road Friction Estimation Part II Report, [http://www.ivss.se](http://www.ivss.se)

US Department of Transportation – Federal Highway Administration


Thanks for your attention