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]

## Table: Automation Levels

<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, using information about the driving environment and 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 acceleration, using information about the driving environment and 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 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>

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

Reference: [SAE, 2014]

Figure 2: Volvo external steering [22]
“Function Architecture” for vehicle motion & energy

**Vehicle Environment**

- Environment observations

**Vehicle Motion Management**

- **Route Management**
  - Estimates, Confidence
  - velocities

- **Traffic Situation Management**
  - accelerations

- **Vehicle Motion Management**
  - Wheel torques, axle steering angles

**Motion Support Device Management**

- from human driver devices

**Human Machine Interface**

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

- Physical models:
  - velocity & energy
  - motion relative lane & traffic
  - motion & individual tyre forces

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

- Sub-system/actuator models:

- Route Management
- Traffic Situation Management
- Vehicle Motion Management
- Motion Support Device Management
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**
- Situation assessment
- Exit ramp
- Candidate manoeuvres
- Candidate trajectories
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)
- ...
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: \( \approx 7 \text{ - } 120\text{t} \) (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

Vehicle Longitudinal and Lateral Control
- Smooth and logical transitions between automated and manual modes
- Robust and fault tolerant control
- Low motion sickness
- High trust and driving comfort

Vehicle Motion State Estimation
- High availability
- High confidence estimates
- Robust and fault tolerant estimation
- High precision positioning
- Presence of road condition estimates

Robust, Independent and Fault Tolerant Vehicle Systems
- Sensors, control units and communication
- Electric power generation, storage and distribution
- Actuation of steering, propulsion and braking
- Condition monitoring

Development Processes
- System safety design process
- Developed requirements
- Robust and fault tolerant design
- Verified product at all levels
- Definition of operational domain
- Rapid feedback test methods

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*

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

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

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

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

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

Kinetic and kinematic models

Pre-processing

Tyre forces
Tyre slip

Friction estimator

Wheel speeds, Inertial Meas. Syst. Steering angle

Normalized traction force

Slip
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
Motion Devices, Virtual Verification, Wheel Model, Bengt Jacobson
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

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

Explicit form modelling
Mathematical modelling
Physical modelling

Computation/Simulation → Interpret results, judge model validity

Virtual Verification

Real world
Theoretical world

≈ODE
≈DAE (Modelica)
≈Drawing
Wheel model as example

$(1 + 3 + 4 + 2 + 3) \cdot 2 = 26$ wheels

104 tonnes, 33 m
Wheel model use cases

Control Longitudinal vehicle translation

Control Longitudinal wheel rotation

Mechatronic Wheel

Brake Actuator and Actuator Control

$T_{ibCReq}$

$S_{IxAbsMaxReq}$

$t_{delay}$,

$t_{sample}$

Mechanical Wheel

Tyre parameters
Wheel model, Mechanical challenges

**Continuously Renewed Friction Surfaces**

\[ F_x = C_x \cdot s_x; \]

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

**Relative Velocity Direction**

\[ s_{xy} = \frac{\sqrt{(R \cdot \omega - v_x)^2 + v_y^2}}{|R \cdot \omega|}; \]

\[ \theta_{Fxy} = \text{arctan2}(-v_y, (R_w \cdot \omega - v_x)); \]

**Dry Friction in Brake**

\[ J \cdot \dot{\omega} = T - F_x \cdot R - T_R; \]

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

**Rolling Resistance**

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

**Multiple wheels**

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/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