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]

Reference: [SAE, 2014]

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

> **Figure 2:** Volvo external steering [22]

<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>Faultback 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, 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 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

Vehicle Motion Management

Traffic Situation Management

Motion Support Device Management

Route Management

Traffic Situation

Motion Support Devices

Vehicle Environment observations

Estimates, Confidence

velocities

accelerations

wheel torques, axle steering angles

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

Vehicle Environment

Route Management

Traffic Situation Management

Vehicle Motion Management

Motion Support Device Management

Human Machine Interface
Next speakers

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

- 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)
- ...
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: $7 - 120t$ (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
Challenges for VMM

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

Vehicle Motion State Estimation
- High availability
- High confidence estimates
- 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
- Condition monitoring
- Actuation of steering, propulsion and braking

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

 Tyre forces
 Tyre slip

Friction estimator

\[ \hat{\mu} \]

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure.png}
\end{figure}
Features and correlation to friction

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

Real world

Theoretical world

Explicit form modelling

Mathematical modelling

Physical modelling

Formulate engineering task (problem)

Initial Design

Re-Design

Evaluate requirement fulfilment

OK

NOK

Final Design

Interpret results, judge model validity

Computation/Simulation

Virtual Verification

≈ ODE

≈ DAE (Modelica)

≈ Drawing

Real-world testing

OK

Final Design

OK

NOK

Evaluate requirement fulfilment

Re-Design

Initial Design

Formulate engineering task (problem)
Wheel model as example

(1 + 3 + 4 + 2 + 3) \cdot 2 = 26 \text{ wheels}

104 \text{ tonnes, 33 m}
Wheel model use cases

Control Longitudinal vehicle translation

Control Longitudinal wheel rotation

Wheel (Mechatronic Wheel) including:
- Brake Actuator and Actuator Control
- Tyre parameters

Vehicle translation components:
- $T_p + T_b$
- $\omega$
- $v_x$, $v_y$

Wheel rotation components:
- $T_iR$
- $F_x$, $F_y$, $F_z$

Mechanical Wheel components:
- $F_{ibPist}$
- $F_{ibPist}$
- $F_{iz}$
- $F_{iy}$
- $F_{iw}$
- $\omega_i$
- $v_{ixw}$, $v_{iwy}$

Internal variables:
- $T_{ibCReq}$
- $S_{ixAbsMaxReq}$
- $T_{ipActl}$
- $v_{ixwActl}$
- $\omega_{lsampled}$

Control parameters:
- $t_{delay}$
- $t_{sample}$

Tyre parameters:
- $R$, $J_w$
Wheel model, Mechanical challenges

Continuously Renewed Friction Surfaces

Relative Velocity Direction

Dry Friction in Brake

Rolling Resistance

Multiple wheels

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

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

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

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

Vehicle Motion

Motion Support Device

Device Management

Vehicle Environment

Traffic Situation Management, TSM

Vehicle Motion Management, VMM

Traffic Situation Management, TSM

Vehicle Motion Management, VMM

Mecha

tronic

Actuator

wheels

absolut

position

relative

position

Suspension and Vehicle Body

Vehicle Environment

Propulsion Actuator with Actuator Control

Brake Actuator with Actuator Control

Mechanical Wheel

Steering Actuator with Actuator Control
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.


http://www.ep.liu.se/ecp/article.asp?issue=157%26article=74

https://saemobilus.sae.org/content/j3016_201401

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

US Department of Transportation – Federal Highway Administration


Thanks for your attention