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>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 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: [Matthijs Klomp, et al, 2019]

Figure 2.: Volvo external steering [22]

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

- Route Management
  - Estimates, Confidence
  - Status, Capabilities, Requests

- Traffic Situation Management
  - Velocities
  - Accelerations
  - Environment observations

- Vehicle Motion Management
  - Wheel torques, axle steering angles

- Motion Support Device Management

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

- Vehicle Environment
  - Route Management
    - Physical models:
      - velocity & energy
      - fuel / SOC
    - data-driven models:
      - macro traffic
    - sub-system/actuator models
      - motion relative lane & traffic
      - motion & individual tyre forces
  - Human Machine Interface
    - motion & individual tyre forces
  - Traffic Situation Management
    - motion relative lane & traffic
    - data-driven models:
      - drivers
      - micro traffic
    - sub-system/actuator models
      - motion relative lane & traffic
  - Vehicle Motion Management
    - motion relative lane & traffic
    - data-driven models:
      - estimators
    - sub-system/actuator models
      - motion relative lane & traffic
  - Motion Support Device Management
    - data-driven models:
      - drivers
    - sub-system/actuator models
      - motion relative lane & traffic
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
- 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**
- Robust control
- Thrust and comfort
- Transitions between driving modes

**Functional safety**
- Candidate manoeuvres
- Exit ramp
- 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)
- ...
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): \( v_x, v_y, \psi_1 \)
  - 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 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
- 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*

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

Assumed friction | True friction
--- | ---
Low (snow) | High (dry asphalt)

- **Low (snow)**: Vehicle speed can be adapted to friction
- **High (dry asphalt)**: False slippery warnings
- **False slippery warnings**
- **AD Vehicle will drive unacceptably slow (not transport efficient)**
- **AD Vehicle will drive too fast (not safe)**
- **High frequency of accidents**
- **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

Pre-processing

Tyre forces
Tyre slip

Friction estimator

\( \hat{\mu} \)

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\( \hat{\mu} \)
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
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

- Explicit form modelling
- Mathematical modelling
- Physical modelling

1. Formulate engineering task (problem)
2. Initial Design
3. Computation/Simulation
4. Interpret results, judge model validity
5. Evaluate requirement fulfilment
6. Re-Design
7. OK: Final Design
8. NOK: Re-Design
9. Real-world testing

Real world

Theoretical world

- ODE
- DAE (Modelica)
- Drawing

Virtual Verification
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 model use cases

Control Longitudinal **vehicle** translation

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

Continuously Renewed Friction Surfaces

Relative Velocity Direction

Dry Friction in Brake

Rolling Resistance

Multiple wheels

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

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

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

Vehicle Motion
Management
Motion Support
Device
Vehicle Environment
Traffic Situation
Management
Vehicle Motion
Management
Route Management
Human Machine Interface
Environment (other vehicles, lane edges, …)
Mechatronic Sensor
Mechatronic Actuator
wheels
absolute position
relative position
suspension
body
Mechatronic Wheel
Brake Actuator with Actuator Control
Mechanical Wheel
Propulsion Actuator with Actuator Control
Suspension and Vehicle Body
Vehicle Environment
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.


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