Vehicle automation modelling and simulation

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This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 723390
Vehicle/Driver Models for (C)AVs

- **Car-following**
  - Adaptive Cruise Control (ACC)
  - Cooperative Adaptive Cruise Control (CACC)

- **Lane changing**
  - Parametrized SUMO lane change model → Automated Vehicles (AVs)
  - Cooperative lane changing → Cooperative and Automated Vehicles (CAVs)

- **Control Transitions (automated ↔ manual)**
  - Transition of Control (ToC) process → Downward & Upwards transitions
  - Minimum Risk Maneuver → Unsuccessful ToCs
Car-following

● (Cooperative) Adaptive Cruise Control – California PATH

i. **Speed control mode**: is designed to maintain the desired driver speed,

ii. **Gap control mode**: aims to maintain a constant space/time gap between the controlled vehicle and its predecessor,

iii. **Gap-closing control mode**: enables the smooth transition from speed control mode to gap control mode,

iv. **Collision avoidance mode**: prevents rear-end collisions.
Lane Changing

- **Parametrized SUMO Lane Change Model**
  
i. **Variance based sensitivity analysis** → Influential lane change calibration parameters
  
ii. **SUMO lane change output vs HMETC lane change data** → Reconciliation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Leader gap (ego lane)</th>
<th>Leader gap (target lane)</th>
<th>Follower gap (target lane)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$S_t$ [%]</td>
<td>$S_t$ [%]</td>
<td>$S_t$ [%]</td>
</tr>
<tr>
<td>Sensitivity Index</td>
<td>$ST_i$ [%]</td>
<td>$ST_i$ [%]</td>
<td>$ST_i$ [%]</td>
</tr>
<tr>
<td>$lcStrategic$</td>
<td>0.39</td>
<td>0.74</td>
<td>1.14</td>
</tr>
<tr>
<td></td>
<td>0.62</td>
<td>2.62</td>
<td>0.47</td>
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<tr>
<td>$lcKeepRight$</td>
<td>1.08</td>
<td>3.32</td>
<td>1.13</td>
</tr>
<tr>
<td></td>
<td>0.83</td>
<td>7.57</td>
<td>2.26</td>
</tr>
<tr>
<td>$lcSpeedGain$</td>
<td>0.90</td>
<td>10.92</td>
<td>0.77</td>
</tr>
<tr>
<td></td>
<td>8.12</td>
<td>22.26</td>
<td>1.37</td>
</tr>
<tr>
<td>$lcAssertive$</td>
<td>59.15</td>
<td>61.26</td>
<td>91.40</td>
</tr>
<tr>
<td></td>
<td>77.03</td>
<td>80.17</td>
<td>95.56</td>
</tr>
</tbody>
</table>

**Negative Relative Speed**

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TransAID Final Event | 1st July 2020
Cooperative Manoeuvring

Decentralized Approach
- Local Coordination
- Sub-optimal Performance
- V2V Communication

Centralized Approach
- Enhanced Perception
- Global Coordination
- Optimal Performance
- V2X Communication
Cooperative Lane Changing

- Decentralized approach
- Cooperation between ego CAV & target follower CAV → **Gap Creation**
- **openGap TraCI function** →
  [https://sumo.dlr.de/wiki/TraCI/Change_Vehicle_State#open_gap](https://sumo.dlr.de/wiki/TraCI/Change_Vehicle_State#open_gap)

### Open Gap Function

<table>
<thead>
<tr>
<th>Parameter Name</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>newTimeHeadway</td>
<td>4 s</td>
<td>The vehicle’s desired time headway will be changed to the given new value with use of the given change rate.</td>
</tr>
<tr>
<td>newSpaceHeadway</td>
<td>15 s</td>
<td>The vehicle is commanded to keep the increased headway for the given duration once its target value is attained.</td>
</tr>
<tr>
<td>duration</td>
<td>5 s</td>
<td>The time period in which the time and space headways will be changed to the given new values.</td>
</tr>
<tr>
<td>changeRate</td>
<td>0.5</td>
<td>The rate at which the new headways’ effectiveness is gradually increased.</td>
</tr>
<tr>
<td>maxDecel</td>
<td>1 m/s²</td>
<td>The maximal value for the deceleration employed to establish the desired new headways.</td>
</tr>
<tr>
<td>referenceVehicleID</td>
<td>ID #</td>
<td>The ID of the reference vehicle.</td>
</tr>
</tbody>
</table>
Control Transitions

State transitions for the take-over Process

Automated mode

- Normal operation
- Prepare ToC
- MRM

TOR

Manual mode

- Post-ToC Recovery
- Normal operation

Downward ToC / Upward ToC
Transition of Control

General CF Model:
\[ \dot{x}(t) = v(t) \]
\[ \dot{v}(t) = a(\Delta x(t), \Delta v(t)) \]

Perceived quantities:
\[ \Delta \ddot{x} = \Delta x + \eta_x \]
\[ \Delta \ddot{v} = \Delta v + \eta_v \]

Erroneous CF Model:
\[ \dot{x}(t) = v(t) \]
\[ \dot{v}(t) = a(\Delta \ddot{x}(t), \Delta \ddot{v}(t)) \]
Minimum Risk Maneuver

i. **MRM** → Current lane

ii. **MRM** → Right-most lane (including lane change maneuver)

iii. **MRM** → Constant deceleration rate (3.0 m/s²)
Triggering of Take-over Requests (TORs)

- **Fixed TOR location** → Specified through TraCI function

- **Dynamic TOR triggering** → Induced by static blockage (e.g. road works etc.)
  - CAV merging to open lane blocked by neighboring traffic
  - $\text{dynamicToCThreshold} \times \text{currentSpeed} + \text{MRM}_{\text{dist}} < \text{distanceToBlockage}$
  - Situation-specific available lead time

- **ToC Preparation Phase** → Open gap TraCI function
  - Establish safe gap to leading vehicle prior to downward control transition

- **Lane Change Abstinence during:**
  - ToC Preparation Phase
  - Recovery Phase
Simulated Use Cases

Service 1: Prevent ToC/MRM by providing vehicle path information

Service 2: Prevent ToC/MRM by providing speed, headway and/or lane advice

Service 3: Prevent ToC/MRM by traffic separation

Service 4: Manage by guidance to safe spot

Service 5: Distribute ToC/MRM by scheduling ToCs
## Mixed Traffic Simulations

### Vehicle Types

<table>
<thead>
<tr>
<th>Vehicle type</th>
<th>Share on urban roads</th>
<th>Share on motorways</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passenger vehicle</td>
<td>87%</td>
<td>77%</td>
</tr>
<tr>
<td>LGV</td>
<td>10%</td>
<td>10%</td>
</tr>
<tr>
<td>HGV</td>
<td>3%</td>
<td>13%</td>
</tr>
</tbody>
</table>

### Automation/Communication Penetration

<table>
<thead>
<tr>
<th>Vehicle Mix</th>
<th>Class 1 (Conn.)</th>
<th>Class 1 (Conn.)</th>
<th>Class 2 (Conn.)</th>
<th>Class 2 (Conn.)</th>
<th>Class 3 (Conn.)</th>
<th>Class 3 (Conn.)</th>
<th>Class 4 (Conn.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>60%</td>
<td>10%</td>
<td>-</td>
<td>15%</td>
<td>-</td>
<td>15%</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>40%</td>
<td>10%</td>
<td>-</td>
<td>25%</td>
<td>-</td>
<td>25%</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>10%</td>
<td>10%</td>
<td>-</td>
<td>40%</td>
<td>-</td>
<td>40%</td>
<td>-</td>
</tr>
</tbody>
</table>

### Traffic Demand Levels

<table>
<thead>
<tr>
<th>Facility Type</th>
<th>Capacity (veh/h/l)</th>
<th>Level of Service (LOS)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>B</td>
</tr>
<tr>
<td>Urban (50km/h)</td>
<td>1500</td>
<td>825</td>
</tr>
<tr>
<td>Rural (80 km/h)</td>
<td>1900</td>
<td>1045</td>
</tr>
<tr>
<td>Motorway (120 km/h)</td>
<td>2100</td>
<td>1155</td>
</tr>
<tr>
<td>Intensity / Capacity (IC) ratio</td>
<td>0.55</td>
<td>0.77</td>
</tr>
</tbody>
</table>

### Parametrization Schemes

<table>
<thead>
<tr>
<th>Parametrization Scheme</th>
<th>ACC Desired time headway</th>
<th>SL2015 Desired longitudinal gaps</th>
<th>ToC/MRM Driver response time</th>
<th>ToC/MRM Post ToC driver performance</th>
<th>ToC/MRM MRM likelihood</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pessimistic Safety (PS)</td>
<td>Small</td>
<td>Short</td>
<td>Long</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Pessimistic Efficiency (PE)</td>
<td>Large</td>
<td>Large</td>
<td>Long</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Moderate Safety and Efficiency (MSE)</td>
<td>Moderate</td>
<td>Moderate</td>
<td>Moderate</td>
<td>Moderate</td>
<td>Moderate</td>
</tr>
<tr>
<td>Optimistic Efficiency (OE)</td>
<td>Small</td>
<td>Short</td>
<td>Short</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Optimistic Safety (OS)</td>
<td>Large</td>
<td>Large</td>
<td>Short</td>
<td>High</td>
<td>Low</td>
</tr>
</tbody>
</table>
Results

- **Work Zone Use Case → Motorway Network**

- **Impacts of vehicle disengagements on Traffic Efficiency**
Results

- Impacts of vehicle disengagements on **Conflict Risk** → Critical Events: Time-to-Collision ≤ 1.5 sec

  - **Uncongested conditions**
  - **Congested conditions**
Findings

• **Transitions of Control (ToCs) →** traffic flow disruption for increased car-following headways in the ToC preparation phase
  - disruption escalates in case of CACC driving, increased share of CAVs in the fleet mix, occurrence of multiple ToCs within narrow temporal window and spatial domain

• **Unmanaged Minimum Risk Manoeuvers (MRMs) →** increased traffic breakdown probability
  - magnitude of the disruption is affected by the driver response time

• **Conservative CAV lane changing →** higher traffic heterogeneity
  - throughput reduction for increased share of CAVs in the fleet mix
  - conflict risk increase in the proximity of lane drop locations
Considerations

• **Transitions of Control (ToCs)** → unavailability and scarcity of field data
  - erratic vehicle behavior during the post-ToC phase explicitly concerns longitudinal motion
  - unexpectedness of ToCs/MRM for manually driven vehicles is not captured comprehensively

• **Mixed traffic** → ambiguous interactions of manually driven vehicles with CAVs
  - low penetration rate of CAVs in the real-world fleet mix

• **Conservative CAV lane changing** → single prototype AV
  - highly automated driving might enable human-like (less conservative) lane changing

• **Simulation Experiments** → abstract simulation networks and hypothetical demand scenarios
Research Outlook

• Accuracy of CAV-human interactions
  ➢ how to quantify behavioral processes during vehicle disengagement?

• Vehicle dynamics and characteristics
  ➢ what are the actual sensing, perception, planning, manoeuvring capabilities of highly automated vehicles?

• Inter-vehicle interactions
  ➢ how are CAVs going to interact with manually driven vehicles?
  ➢ how are CAVs equipped with different automation and communication capabilities are going to interact with each other?

Need for Empirical Evidence!
Integration of Models in SUMO

- **(Cooperative) Adaptive Cruise Control Model** → SUMO Source Code
  - https://sumo.dlr.de/wiki/Car-Following-Models/ACC (Sumo Wiki Page)
  - `<SUMO_HOME>/src/microsim/cfmodels/MSCFModel_ACC.cpp`
  - https://sumo.dlr.de/wiki/Car-Following-Models/CACC (Sumo Wiki Page)
  - `<SUMO_HOME>/src/microsim/cfmodels/MSCFModel_CACC.cpp`

- **Parametrized Lane Change Model** → Adaptation of existing model params

- **Cooperative lane changing** → Open gap TraCI function
  - https://sumo.dlr.de/wiki/TraCI/Change_Vehicle_State#open_gap_.280x16.29

- **ToC/MRM Model** → ToC Device (SUMO Source Code + TraCI Functions)
  - https://sumo.dlr.de/wiki/ToC_Device (Sumo Wiki Page)
Publications

• **Deliverable D3.1** → Modelling, simulation and assessment of vehicle automations and automated vehicles’ driver behaviour in mixed traffic

• **Deliverable D3.2** → Cooperative manoeuvring in the presence of hierarchical traffic management


Questions? Let’s stay in touch!

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