A Hierarchical Model-based Optimization Control Method for Merging of Connected Automated Vehicles

Na Chen, Meng Wang, Tom Alkim, Bart van Arem
Background

- Vehicle-to-Vehicle communication
- Vehicle-to-Infrastructure communication

Connected Automated Vehicle (CAV)

- Traffic capacity increase (efficiency)
Which slot is the **best option** for the on-ramp vehicle to merge?

How to generate **optimal trajectories** then?
Relevant research

Existing methods:

1. **Mapping**

Control zone’s exit boundary

Times-to-go comparison: 2. **Heuristic approach**

Control zone’s entry boundary

Passing time comparison: 3. **First-in-first-out**

4. **Optimization control method:**

   Predefining vehicle geometrical lotus or not
Research objective

**Objective:** to design an efficient and safe control strategy for merging of CAVs.

A CAV system

- Centralized control method
- Model-based optimization
Upper level controller

State variable $X^u$: vehicle positions $x_i$ and speeds $v_i$

Control variable $U^u$: future vehicle order $r$ and on-ramp vehicle’s lane change preparation time $l_p$.

Vehicle dynamics: $\frac{dx}{dt} = v; \frac{dv}{dt} = a$

Car-following mode: $a_i = C_1 \cdot \Delta s_i + C_2 \cdot \Delta v_i$ (Helly model)

\[ \Delta s_i = \text{Real gap} - \text{desired gap} \left( v_i \cdot t_d + s_0 \right); \ \Delta v_i \text{ relative speed} \]

Cooperation mode: if $x_{i-1} < x_i$, $a_{i-1} = a_{com}$ accelerate and $a_i = d_{com}$ decelerate

1) $\Delta s_{r}(d_t)$ and $\Delta s_{r-1}(d_t)$ are large enough
2) $a_r(d_t), a_{r-1}(d_t) \in [d_{com}, a_{com}]$
Upper level controller

Objective function

\[
\min_{l_p,r} \int_{t_1}^{t_1+T} \left( c_1 \sum_{i=1}^{N} (\Delta s_i)^2 + c_2 \sum_{i=1}^{N} (\Delta v_i)^2 + c_3 \sum_{i=1}^{N} (a_{ix})^2 \right) dt
\]

Subject to:

1. \( a_i \in [a_{\min}, a_{\max}] \);
2. \( v_i \in [0, v_{\text{limits}}] \);
3. \( r \in \{2,3,..,N-1\} \);
4. Car-following mode and cooperation mode
5. Vehicle dynamics
6. The on-ramp vehicle completes lane changing when it is on the acceleration lane

Quadratic mixed integer programming problem
Lower level controller

Model Predictive Control (MPC)

An objective function

Optimizer
An explicit Model

Independent variables;
\[ t \in [t_0, t_0 + T_p] \]

Measurements \((t_0)\)

Plant

Output \(t = t_0 + \Delta t\)

A new cycle \(t_0 = t_0 + \Delta t\)

State variable \(X^l\): vehicle positions \(x_i\) and speeds \(v_i\)

Control variable \(U^l\): Vehicles’ longitudinal accelerations \(a_{ix}\) and on-ramp vehicles’ lane change initiation time \(l_t\)
Lower level controller

**Objective function**

\[
\min_{U^1[t_0, t_0+T_p]} \int_{t_0}^{t_0+T_p} L(X^1, U^1) \, dt
\]

\[
L = c_1 \sum_{i=1}^{N} \left( \Delta s_i \right)^2 + c_2 \sum_{i=1}^{N} \left( \Delta v_i \right)^2 + c_3 \sum_{i=1}^{N} \left( a_{ix} \right)^2
\]

- Safety
- Efficiency
- Control

To reach equilibrium states
To have smooth accelerations

\[ l_t : \Delta s_r(l_t) \text{ and } \Delta s_{r-1}(l_t) \text{ are large enough to change lane} \]

**Trajectory equation:** to generate lateral motion for the merging vehicle

Subject to same constraints as upper level controller excluding cooperation mode.
Experiment design & Results

Controller parameters:
1) \( t_d = 1 \text{ s} \)
2) \( v_i \in [0, 30] \text{ m/s} \)
3) \( a_i \in [-5, 2] \text{ m/s}^2 \)

Initial states: \( v_i = 25 \text{ m/s} \)

Decision from different methods:
\( r = 4, l_p = 0 \text{ s. (first-in-first-out)} \)
\( r = 3, l_p = 4 \text{ s. (designed upper level controller)} \)
Experiment design & Results

\[ r=4, \quad l_p=0 \text{ s. (first-in-first-out)} \]

\[ l_t=9.6 \text{ s} \]

\[ r=3, \quad l_p=4 \text{ s. (designed upper level controller)} \]

\[ l_t=8.2 \text{ s} \]
Experiment design & Results

<table>
<thead>
<tr>
<th>r=3, l_p=4 s</th>
<th>r=3, l_p=3 s</th>
<th>r=4, l_p=0 s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper level</td>
<td>283,97</td>
<td>290,38</td>
</tr>
<tr>
<td>Lower level</td>
<td>1725,08</td>
<td>1932,726</td>
</tr>
</tbody>
</table>

Comparison: **16.60 %** decrease

**Table 1** Objective function values comparison

Advantages of the proposed control method:
1. to consider the lane change preparation time
2. to choose a reasonable vehicle order
3. to have small sizes of dimension for control variables
Conclusion

The proposed control method

✓ vehicle order + lane change preparation time
✓ safe and efficient trajectories for CAVs

Future research direction

➢ Multiple mainstream lanes
➢ Mixed traffic
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