A Model Predictive-based Approach for Longitudinal Control in Autonomous Driving with Lateral Interruptions

Kai Liu, Jianwei Gong, Arda Kurt, Huiyan Chen, and Ümit Özgüner
Intelligent Vehicle Research Center, Beijing Institute of Technology, and Center for Automotive Research, The Ohio State University

Introduction

The longitudinal control of an autonomous vehicle usually suffers from lateral interruptions, such as the cutting in/out of the lead vehicle, deteriorating its performance and even endangering driving safety.

To address this problem, we present a model predictive-based approach for longitudinal control in autonomous driving by taking the lateral interruptions into account. First, a virtual lead vehicle scheme is introduced to predict the future behavior of the actual lead vehicle. By following the virtual lead vehicle rather than the actual lead vehicle, the control of the host vehicle is simplified to keep a proper following gap problem. Then, a strategic car-following gap (CFG) model, generated from highway naturalistic driving data, is employed to describe the safety hazard and the probability of cut-ins by other vehicles. A model predictive controller, incorporating the strategic CFG model as well as the acceleration and jerk limitations in the objective function, is designed for the longitudinal control of the host vehicle. Solving the optimal control problem can not only smooth the oscillation and overshoots caused by the lateral interruptions but also reduce the probability of cut-ins from the adjacent lanes.

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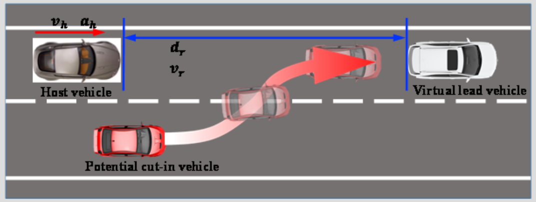
Contact

For more information, please contact
liu.5458@osu.edu,
gongjianwei@bie.edu.cn,

Problem Statement



Autonomous longitudinal control with lateral interruptions, such as the cutting in/out of leading vehicle, has two main challenges:

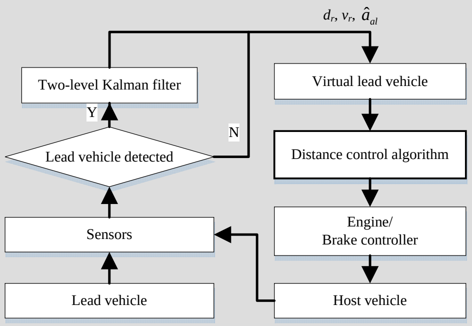
- Lateral interruptions interfere with the smoothness of traffic flow, leading to speed oscillation or overshoots which would endanger the autonomous vehicle.
- Lateral interruptions arose a dilemma when following a preceding vehicle: leaving a sufficient car-following gap (CFG) poses an opportunity for other vehicles to cut-in while shortening the CFG increases the likelihood of collision.

Q: How to maintain proper CFGs that ensure safety distances in the longitudinal direction and, meanwhile, avoiding cut-ins from the lateral direction?

- Virtual lead vehicle scheme to predict the future behavior of the actual lead
- Car-following gap (CFG) model is generated to describe the safety hazard and the cut-in probability of other vehicles
- Design a model predictive control (MPC) controller for the host vehicle

Virtual lead vehicle scheme

Host vehicle remains in the distance control mode to follow a virtual lead vehicle, instead of tracking the actual lead vehicle.



Block diagram of the virtual lead vehicle scheme

Strategic CFG model

Strategic CFG model is formulated two potential field functions:

$$HI = e^{-\left(d_r / a_{NCI}\right)^{b_{NCI}}} \qquad a_{NCI} = -0.0033v_h^2 + 0.6515v_h - 0.3184 \qquad b_{NCI} = 3.44709$$

$$CIP = 1 - e^{-\left(d_r / a_{CI}\right)^{b_{CI}}} \qquad a_{CI} = -0.0031v_h^2 + 0.6676v_h + 7.4344 \qquad b_{CI} = 3.027836$$

Descriptions:

- Hazard index (*HI*) represents the safety hazard by using the probability of rear-end collision without cut-ins
- Cut-in probability (CIP) reflects the likelihood of cut-ins by other vehicles
- The parameters a_{CI}, a_{NCI}, b_{CI} and b_{NCI} are approximated from highway naturalistic driving data
- *HI* and *CIP* are approximated by convex quadratic functions
- Applied to designing the cost function of the MPC controller

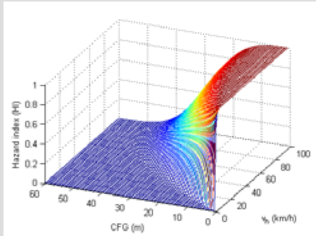


Figure of *HI*

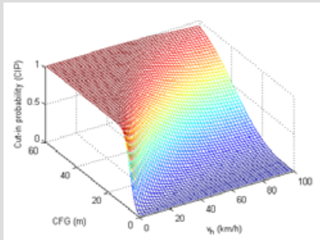


Figure of *CIP*

MPC Controller Design

The MPC controller incorporates the convex quadratic approximated strategic CFG model, as well as limitations on acceleration and jerk:

$$\min_{a_{des},\varepsilon} J = \underbrace{\sum_{k=0}^{Np} \gamma\left(f_{HI}(k) + f_{CIP}(k)\right)}_{\text{find the optimal CFG}}$$

$$\underbrace{+\left\|a_{des}(k)\right\|_{\alpha}^{2} + \left\|a_{des}(k) - a_{des}(k-1)\right\|_{\beta}^{2}}_{\text{minimizes control effort}}$$

$$+\left\|\varepsilon(k)\right\|_{\rho}^{2}$$

$$\text{s. t.} \quad \boldsymbol{\xi}(k+1) = \boldsymbol{A}_h\boldsymbol{\xi}(k) + \boldsymbol{B}_1 a_{des}(k) + \boldsymbol{B}_2 a_{vl}^{p}(k)$$

$$a_{\min} \le a_{des}(k) \le a_{\max}$$

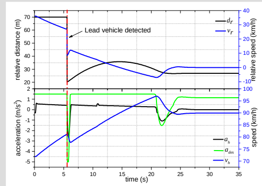
$$\left|a_{des}(k) - a_{des}(k-1)\right| \le j_{\max}$$

$$\boldsymbol{H}_{state}\boldsymbol{\xi}(k) \le \boldsymbol{G} + \varepsilon(k)$$

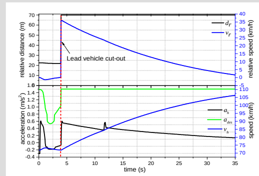
CVXGEN is implemented to generate a solver that allows for real-time implementation.

Simulation Performance

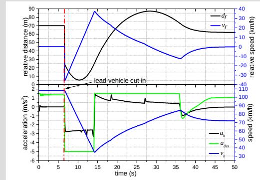
Cut-in scenario: host vehicle is driving at 72km/h. A lead vehicle on the same longitudinal position with the speed of 90km/h on the adjacent lane. The lead vehicle is commanded to cut-in after 5 s.



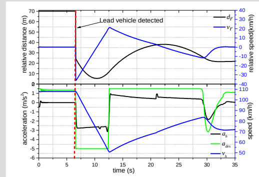
Cut-out scenario: host vehicle and the lead vehicle are driving at 72km/h on the current lane and the speed limit set to be 108km/h. The lead vehicle is commanded to change to the adjacent lane after 5 s.



Cut-in with constant time headway scenario: a constant time headway model is applied in the longitudinal controller. The constant time is set to be 3 seconds. All the other settings are the same with the cut-in scenario.



Emergency cut-in scenario: host vehicle is driving at the speed limit, 108km/h. A lead vehicle with the speed of 72km/h on the adjacent lane, commanded to cut-in after 5 s. The relative longitudinal distance is 90 m.



Conclusions

A virtual lead vehicle scheme is introduced to predict the future evolution of the actual lead vehicle. Then, a strategic CFG model is employed to account for the safety hazard and the probability of cut-ins, respectively. An MPC-based controller, incorporating the strategic CFG model in the cost function, is designed to find the optimal CFG.

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