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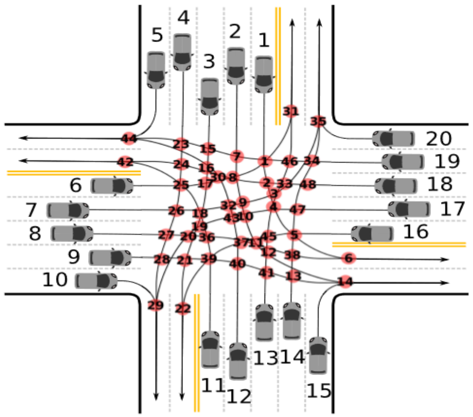
Design and experimental validation of event-triggered multi-vehicle cooperation in conflicting scenarios

Key words: Connected and automated vehicles; Event-triggered control; Nonlinear and uncertain dynamics; Conflicting scenarios

Corresponding authors: Jin HUANG; Yifan JIA
E-mail: huangjin@tsinghua.edu.cn; jiayifan@mail.tsinghua.edu.cn
ORCID: https://orcid.org/0000-0001-8774-2936;
https://orcid.org/0000-0003-4411-8222

Conflicting scenarios

- Resolving traffic problems in conflict zones has significant social and commercial benefits.



Conflicts in traffic movements

Time-varying traffic flow

Traffic problems

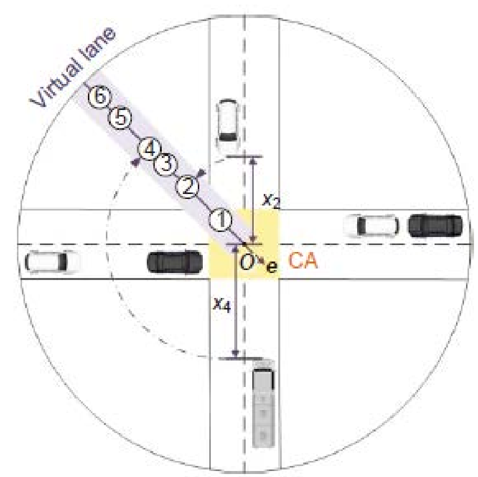
Accidents

Inefficiency

Tendency and challenges

- Tendency: Virtual platooning is a promising technique in coordinating connected and automated vehicles (CAVs) in conflicting scenarios.
- Challenge 1: How to make efficient use of scarce communication resources to enhance the performance of vehicular ad hoc network (VANET)?
- Challenge 2: How to ensure the stability of the multi-vehicle system subject to real-world uncertainties?

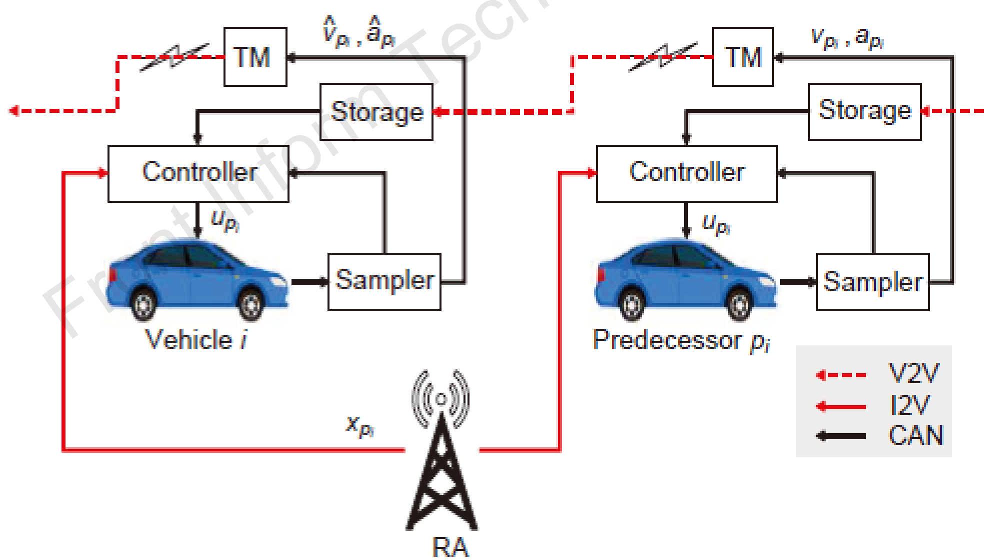
Two-dimensional (2D) conflicting scenario



One-dimensional (1D) virtual platoon

Proposed solution

- Contribution 1: The study adopts the event-triggered control (ETC) mechanism and develops a novel triggering condition which considers the uncertainty of the boundary information.
- Contribution 2: Based on contribution 1, the study further proposes a distributed robust controller for multi-vehicle cooperation in conflicting scenarios.



Architecture of the event-triggered control framework

1) Vehicle model and triggering condition

- The third-order nonlinear longitudinal dynamical model is used to build the multi-vehicle system.
- The triggering condition suggests that the transmission only takes place when the state deviation exceeds the threshold.

$$\begin{cases}\dot{x}_i(t)=v_i(t),\\ \dot{v}_i(t)=\dfrac{1}{M_i}\Big[F_i(t)-\big(\bar{c}_i+\Delta c_i\big(x_i(t),v_i(t),\sigma_i(t),t\big)\big)v_i^2(t)-\big(\bar{f}_i+\Delta f_i\big(x_i(t),v_i(t),\sigma_i(t),t\big)\big)\Big],\\ \dot{F}_i(t)=\dfrac{1}{\tau_i}\big(-F_i(t)+u_i(t)\big).\end{cases}$$

Vehicle dynamics

$$T_{j+1}^{p_i}=\inf_{t\in\mathbb{R}^+}\left\{t>T_j^{p_i}\mid \|\Phi_{p_i}\xi_{p_i}^{\mathrm{T}}(t)\|>\zeta_{p_i}\right\}\qquad \xi_{p_i}(t)=\begin{bmatrix} v_{p_i}(T_j^{p_i})-v_{p_i}(t)\\ a_{p_i}(T_j^{p_i})-a_{p_i}(t)\\ \big(v_{p_i}(T_j^{p_i})-v_{p_i}(t)\big)\,\Pi_i^2\end{bmatrix}^{\mathrm{T}}$$

Weight coefficient | State deviation | Threshold

Triggering condition

2) Robust control design

- The proposed control has an analytical form and can be calculated efficiently in real-world implementation.
- The storage unit reserves the information in the latest transmission. Parameters in the form of $\widehat{(\cdot)}$ use the values in the storage unit.

$$u_i = -\frac{M_i\tau_i}{q_i}\left(h_i\hat{\dot{e}}_i + \hat{\Upsilon}_i + \kappa_i\hat{\beta}_i + \frac{2\mu_i\Pi_i}{|\mu_i| + \epsilon_i}\right) \qquad t \in [T_j^{p_i}, T_{j+1}^{p_i})$$

$$\begin{cases} \hat{\dot{e}}_i(t) = q_i a_i(t) + v_i(t) - v_{p_i}(T_j^{p_i}), \\ \hat{\beta}_i(t) = h_i e_i(t) + \hat{\dot{e}}_i(t), \\ \hat{\Upsilon}_i(t) = -q_i\left[\frac{1}{\tau_i}a_i(t) + \frac{1}{M_i\tau_i}\cdot\left(\bar{c}_i\left(v_i^2(t) + 2\tau_i v_i a_i(t)\right) + \bar{f}_i\right)\right] + a_i(t) - a_{p_i}(T_j^{p_i}) \end{cases}$$

Proposed control

Simulation results

- Results validate that vehicles approaching the intersection can negotiate safely and efficiently with the proposed control.
- An average of 77 sampled data packets are transmitted via the VANET within the cooperation area under the ETC mechanism. The number would be 200 under conventional time-triggered control.

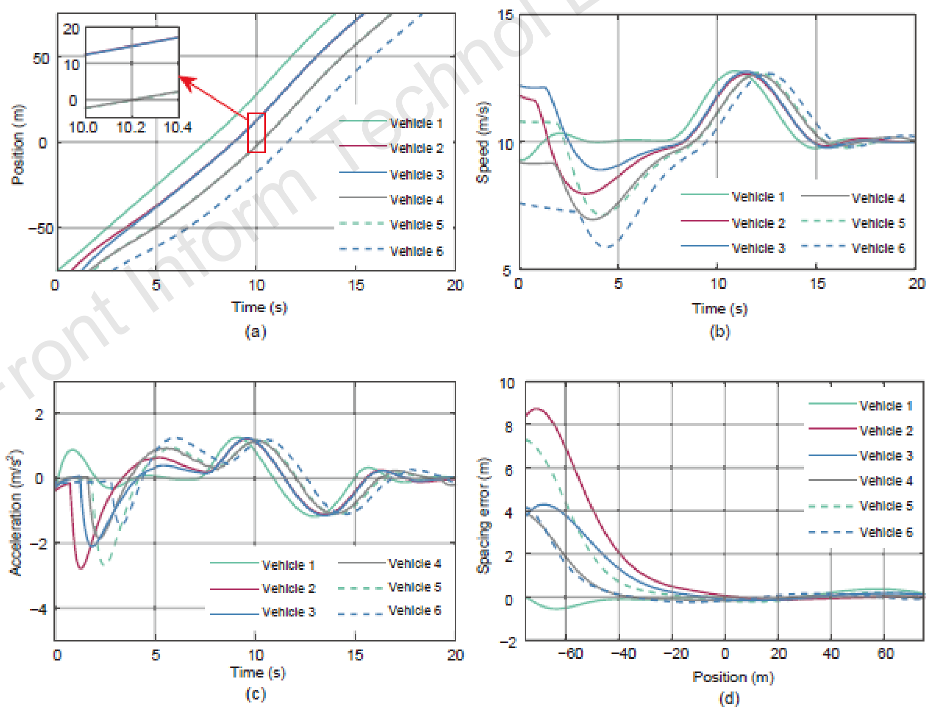
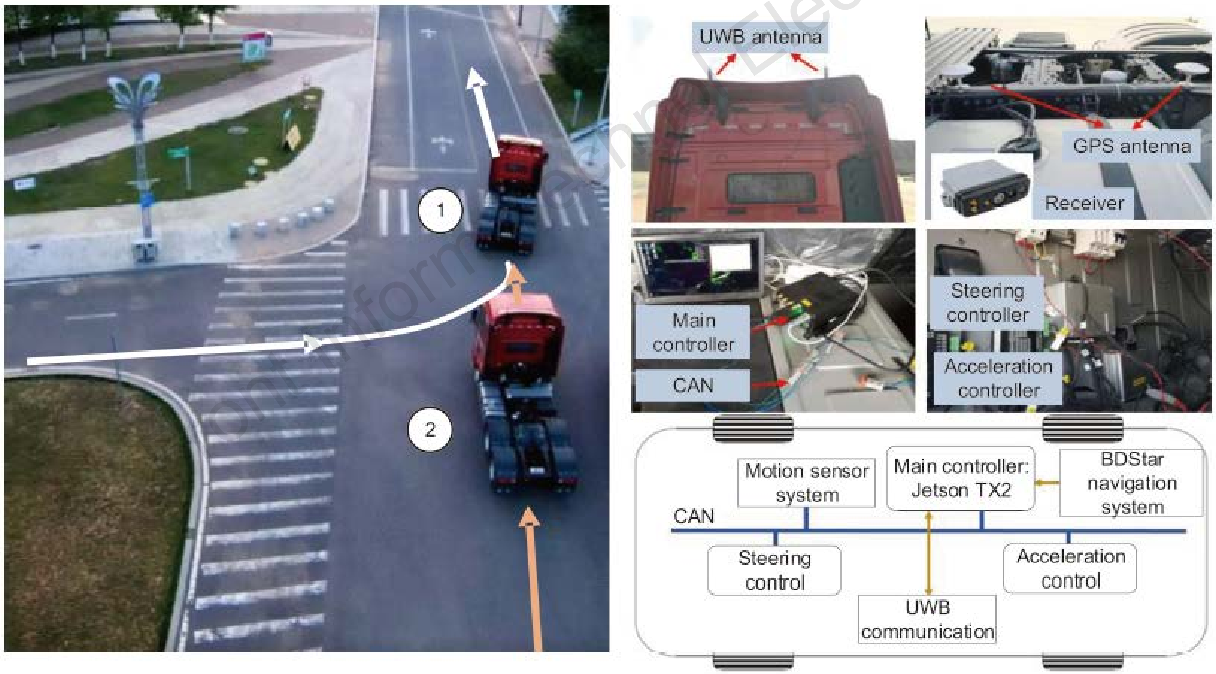


Fig. 4 Results of vehicle motion: (a) position; (b) speed; (c) acceleration; (d) spacing error. References to color refer to the online version of this figure

Experimental setup

- The proposed ETC is validated in Expo Park in Qingdao, China, using two autonomous tractor trucks at the intersection. The test vehicles are JH6 trucks communicating via ultra-wide bandwidth (UWB).



(a) (b)

Fig. 5 Experimental setup: (a) virtual platoon; (b) on-board hardware and software of test vehicles. UWB: ultra-wide bandwidth; GPS: Global Positioning System; CAN: controller area network. References to color refer to the online version of this figure

Experimental results

- The tracking performance shown in Figs. 6b and 6c verifies the effectiveness of the proposed method.
- Considering that vehicles approaching the conflicting scenario tend to drive steadily at a relatively low speed, the proposed method is ready for practical implementation.

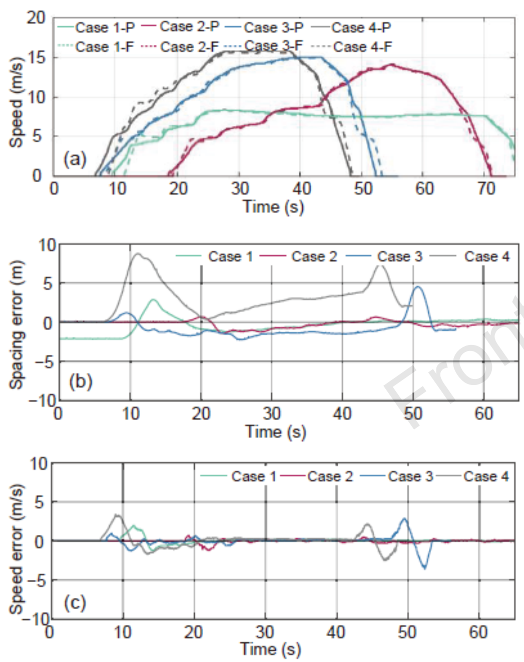


Fig. 6 Vehicle motion and tracking performance: (a) speed; (b) spacing error; (c) speed error. P: predecessor; F: follower. References to color refer to the online version of this figure

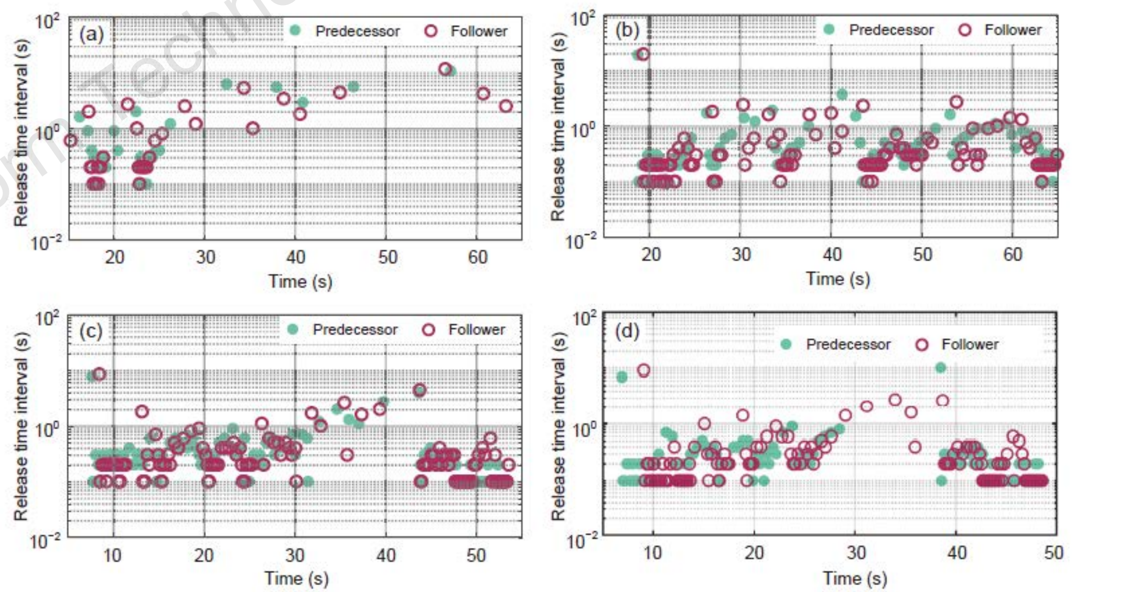


Fig. 7 Transmission instants and release time intervals in the experiments: (a) case 1; (b) case 2; (c) case 3; (d) case 4

Conclusions

1. The proposed event-triggered control can significantly reduce the use of communication resources compared with TTC methods, and hence improves the communication performance.

2. The triggering condition in the proposed method fuses the state error with parametric uncertainty, which has not been proposed or explored in existing ETC studies.

3. The effectiveness of the proposed method is validated in the simulations and experiments. The results indicate that it is readily applicable.

Jin HUANG is an associate professor with School of Vehicle and Mobility, Tsinghua University. He is the principal investigator of one key project, one general project, one outstanding youth fund, one youth fund of the National Natural Science Foundation of China along with six other projects. He has participated in one national major scientific research instrument development project and one National Science and Technology Support Program of the Ministry of Science and Technology, and presided over a horizontal funding of over 130 million CNY. He has published 62 SCI/EI papers, including 32 SCI papers as the first/corresponding author. He has won the Excellent Scientific Paper Award of the sixth China Association for Science and Technology. He has declared 63 national invention patents (ranked the first 43 and the second 8), among which 49 have been authorized (ranked the first 33 and the second 8), and 16 Software copyrights have been approved. He has co-editored 2 books (ranked 2), and has made 5 international conference invited reports. He won the first prize of Dalian Patent Award (ranked 2).