Cooperative Adaptive Cruise Control for Connected Autonomous Vehicles by Factoring Communication-Related Constraints

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1. Introduction

Background:

- Traffic oscillation: "stop and go" or "slow and fast" traffic propagation in traffic flow, which can result in traffic congestion.
- Connected autonomous vehicle (CAV) system enhances the situational awareness and performance through the implementation of more robust system-level vehicle control strategies, especially platoon-based cooperative adaptive cruise control (CACC), which can mitigate the traffic oscillation.

Research gaps:

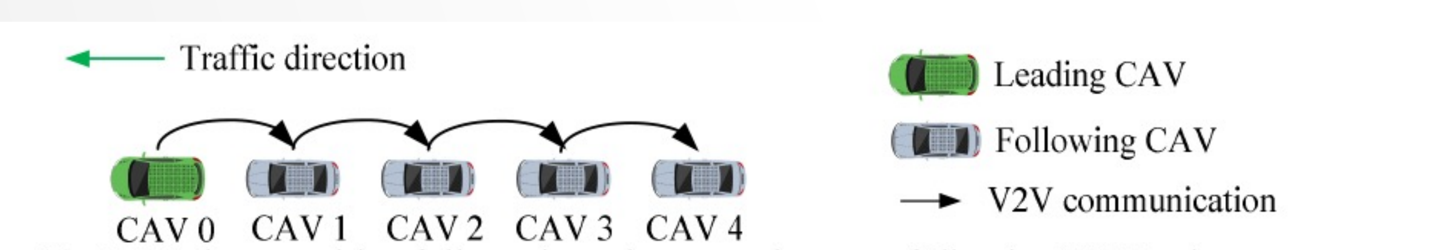
- More communication can improve the performance of CACC but it will lead the increasing of communication failure.
- Most existing studies assume perfect communication conditions without failure, which means the platoon-level information flow topology (IFT) of CACC is fixed (CACC-FIFT).
- The assumption ignores the fact that the VIFT and the IFT can change dynamically due to V2V communication failure.
  - ✓ Some existing literature consider IFT dynamics but in a passive way.
  - ✓ Only uses the information from the functioning links.
  - ✓ The performance is still constrained by the traffic conditions: higher traffic density leads to higher failure probability.

Research objective: Optimize the IFT dynamically by deactivating the communication functionalities of some CAVs in the platoon to achieve a better CACC performance with communication-related constraints.

2. IFT and Degeneration Scenarios

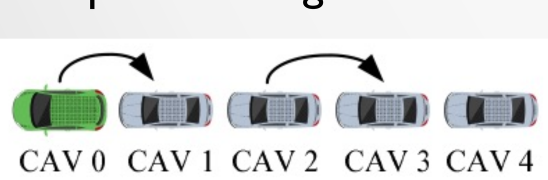
IFT and degeneration scenarios

- Introduce a vector $\xi = [\eta_0, \eta_1, \dots, \eta_N], \eta_i \in \{0,1\}$ for $i = 0,1,\dots,N$ to indicate the IFT of a platoon with $N+1$ vehicles, where η_i indicates the status of the V2V communication device of vehicle i: $\eta_i = 0$, when "send" functionality of V2V communication is deactivated; otherwise, $\eta_i = 1$.



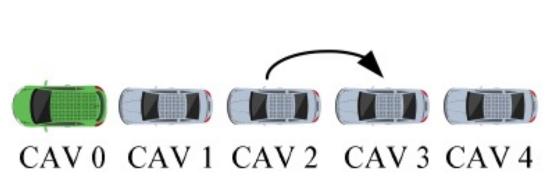
(a). CAV platoon with a fully-activated two-predecessor-following VIFT scheme

For example, the IFT $\xi = [1,0,1,0,0]$ in (b) has four degeneration scenarios: $\xi_1(\xi) = [1,0,1,0,0]$, $\xi_2(\xi) = [1,0,0,0,0]$, $\xi_3(\xi) = [0,0,1,0,0]$ and $\xi_4(\xi) = [0,0,0,0,0]$, which are shown in (b)-(e), respectively. We denote $\mathbf{\Omega_d}(\xi)$ as the set of all possible degeneration scenarios $\xi_d(\xi)$ for IFT ξ.



(b). An example IFT with "send" functionalities of CAVs 1, 3 and 4 deactivated

(c). Degeneration scenario of (b) with CAV 2 failing to send message

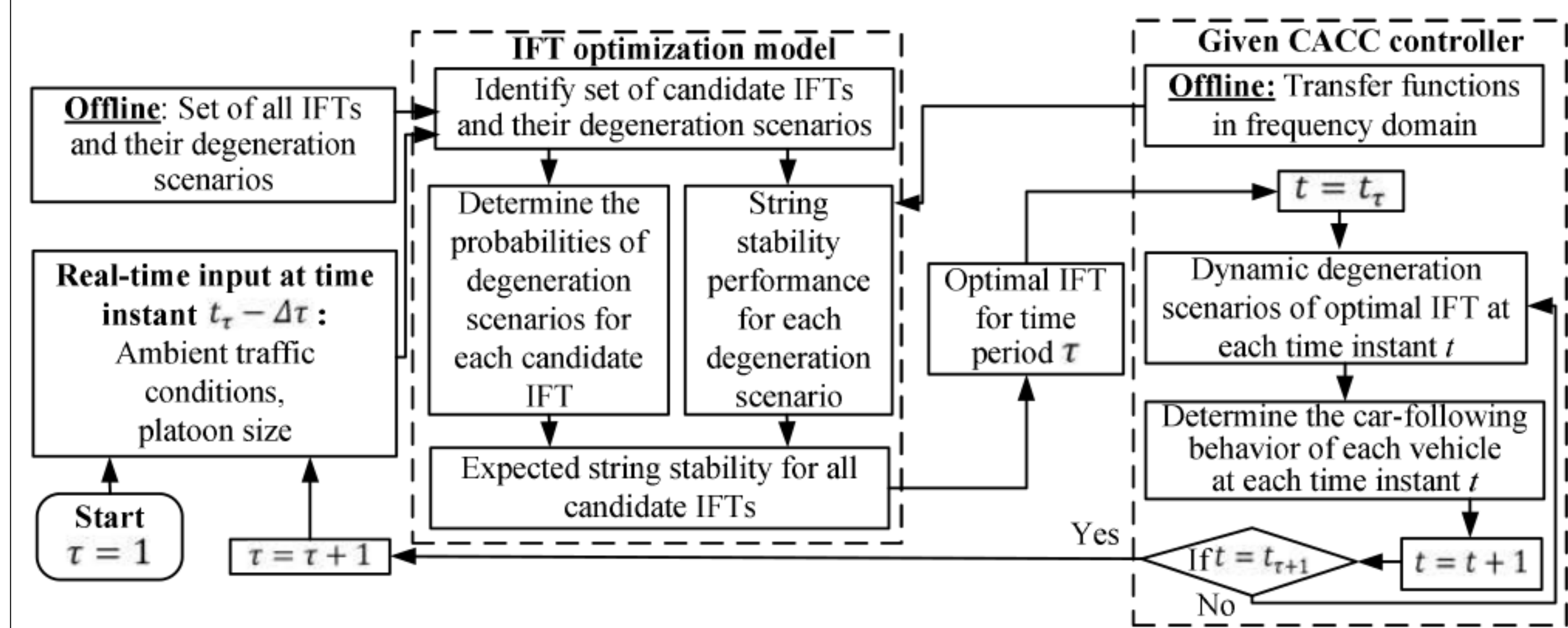


(d). Degeneration scenario of (b) with CAV 0 failing to send message

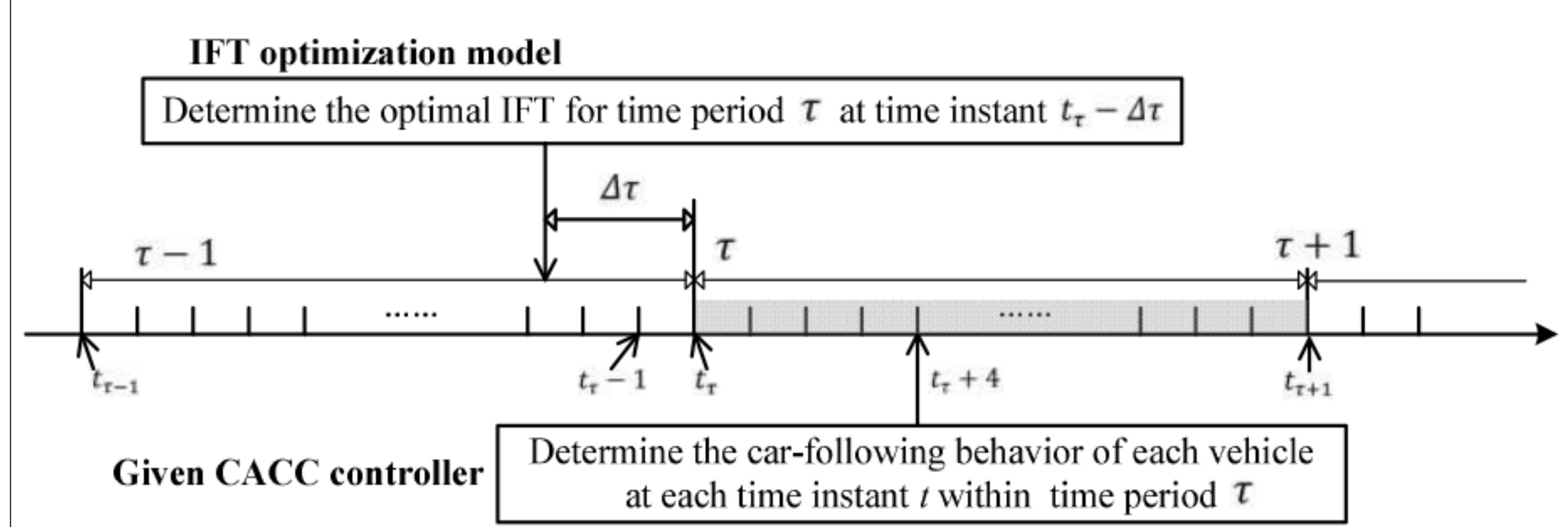
(e). Degeneration scenario of (b) with both CAVs 0 and 2 failing to send messages

3. Main Idea of CACC with Dynamically Optimized IFT

Conceptual Flowchart of CACC-OIFT



Operational Deployment of CACC-OIFT



The proposed CACC-OIFT strategy for a time period seeks to determine the optimal IFT that maximizes the expected string stability by deactivating or activating the "send" functionality of the V2V communication devices of the vehicles in the platoon, and deploys it for every time instant within that period based on the unfolding degeneration scenarios for that IFT due to V2V communication failures.

Main steps:

- Given the ambient traffic conditions and platoon size at some time instant $\Delta\tau$ before the start of time period τ (the period from time instant t_τ to $t_{\tau+1}$ (i.e. $[t_\tau, t_{\tau+1})$), the IFT optimization model first identifies the candidate IFTs corresponding to the platoon size and their degeneration scenarios.
- The ambient traffic conditions are used to determine the probabilities of the degeneration scenarios for each candidate IFT as these traffic conditions determine the V2V (link) communication failure probabilities.
- The string stability for each degeneration scenario for each candidate IFT is obtained from the predetermined string stabilities for all degeneration scenarios for all possible IFTs, computed offline using the transfer function in frequency domain of the given adaptive PD controller
- The optimal IFT (activations and deactivations of "send" functionalities for the platoon vehicles) for time period τ is determined as the candidate IFT which has the maximum expected string stability across all of its degeneration scenarios.

4. Methodology

Main Idea of the Optimization Model

$$\text{OPT-I} \quad \underset{\xi\in\Omega}{\text{OPT}}\; E(\xi) = \sum_{\xi_d(\xi)\in\Omega_d(\xi)} P_d(\xi_d(\xi)) E_d(\xi_d(\xi))$$

$$\begin{aligned}
\text{s.t.} \quad & \xi = [\eta_0, \eta_1, \dots, \eta_N], \eta_i \in \{0,1\} \text{ for } i = 0,1,\dots,N \\
& \mathbf{\Omega} = \{[\eta_0, \eta_1, \dots, \eta_N] | \eta_i \in \{0,1\} \text{ for } i = 0,1,\dots,N \\
& \xi \in \mathbf{\Omega} \\
& \xi_d(\xi) = [\eta_{0,d}, \eta_{1,d}, \dots, \eta_{N,d}], \eta_{i,d} \in \{0,1\}, \eta_{i,d} \le \eta_i \text{ for } i = 0,1,\dots,N \\
& \mathbf{\Omega_d}(\xi) = \{[\eta_{0,d}, \eta_{1,d}, \dots, \eta_{N,d}] \mid \eta_{i,d} \in \{0,1\}, \eta_{i,d} \le \eta_i \text{ for } i = 0,1,\dots,N \\
& \textstyle\sum_{\xi_d(\xi)\in\Omega_d(\xi)} P_d(\xi_d) = 1, \text{ for any } \xi \in \mathbf{\Omega}
\end{aligned}$$

Objective function:

- $P_d(\xi_d(\xi))$ is the probabilities that a platoon with IFT ξ operates under ξ_d (ξ) at a certain time instant.
- $E_d(\xi_d(\xi))$ is the CACC performance of a platoon when operating under ξ_d (ξ). $E(\xi)$ is the expected platoon control performance of IFT ξ with communication-related constraints.

Constraints:

- The first three constraints of OPT-I relate to the decision variable ξ.
  - ✓ The first constraint states that ξ is a binary 0-1 vector.
  - ✓ The second constraint is the set $\mathbf{\Omega}$ of IFTs ξ corresponding to the two-predecessor-following VIFT.
  - ✓ The third constraint states that ξ belongs to $\mathbf{\Omega}$.
- The remaining three constraints correspond to the degeneration scenario $\xi_d(\xi)$.
  - ✓ The fourth constraint shows the relationship between degeneration scenario $\xi_d(\xi)$ and IFT ξ.
  - ✓ The fifth constraint indicates that the set $\mathbf{\Omega_d}(\xi)$ includes all possible degeneration scenarios for IFT ξ.
  - ✓ The last constraint states that the probabilities of the degeneration scenarios for an IFT ξ should sum up to 1.

Speed Oscillation Energy– CACC performance $E_d(\xi_d(\xi))$:

- Traffic oscillation can be measured by speed variance.
- The speed of a vehicle varies as it moves on a highway, which is similar to the case that a signal propagates in medium.
- Introduce speed oscillation energy for vehicle i in frequency domain as signal energy:

$$e_i = \int_0^{+\infty} V_i^2(j\omega)\, d\omega$$

- $V_i\,(j\omega)$ is the speed frequency response which represents the amplitude of the oscillation at specific frequency ω.
- $V_i^2(j\omega)$ is proportional to the energy of this frequency ω.
- Thereby, the oscillation energy of a vehicle is the sum of its energies in all frequencies.

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The speed oscillation energy of a platoon:

$$E_{\boldsymbol{d}}(\xi_{\boldsymbol{d}}(\xi)) = \sum_{i=0}^{N} e_i = \sum_{i=0}^{N}\left[\int_0^{+\infty} V_i^2(j\omega)d\omega\right]$$

- Derive $V_i(j\omega)$ for all vehicles using the leading vehicle trajectory oscillation $X_0(j\omega)$ information (obtained through V2I communications)

$$V_i(j\omega) = 2\pi j\omega \mathrm{SS}_{X,i}(j\omega, \xi_{\boldsymbol{d}}(\xi))X_0(j\omega)$$

$$\mathrm{SS}_{X,i}(j\omega, \xi_{\boldsymbol{d}}(\xi)) = \frac{X_i(j\omega)}{X_0(j\omega)}$$

$$E_d(\xi_{\boldsymbol{d}}(\xi)) = \sum_{i=0}^{N} V_i^2(j\omega)d\omega = 4\pi^2\sum_{i=0}^{N}\int_0^{+\infty}\omega^2 \mathrm{SS}_{X,i}^2(j\omega, \xi_{\boldsymbol{d}}(\xi))X_0^2(j\omega)d\omega$$

Probabilities of Degeneration Scenarios -- $P_d(\xi_{\boldsymbol{d}}(\xi))$:

- In literature, a communication model with saturated and unsaturated communication traffic is developed using a Markov chain.

$$p_{i,unsat}(\xi) = [k_1\log(\bar{\rho}_i(\xi)) + k_2\mathrm{CW} + k_3]p_{i,sat}(\xi)$$

- $\bar{\rho}_i(\xi)$: CAV density around Vehicle I
- CW : Contention window (communication parameter)
- The probability of the degeneration from ξ to $\xi_{\boldsymbol{d}}$ is

$$P_d(\xi_{\boldsymbol{d}}(\xi)) = \prod_{i\in \boldsymbol{A_d}(\xi)} p_{i,\mathrm{unsat}} \prod_{i\in \boldsymbol{B_d}(\xi)}(1 - p_{i,\mathrm{unsat}})$$

Optimization model:

- Substitute $P_d(\xi_{\boldsymbol{d}}(\xi))$and $E_{\boldsymbol{d}}(\xi_{\boldsymbol{d}}(\xi))$ in OPT-I, we have

OPT-II

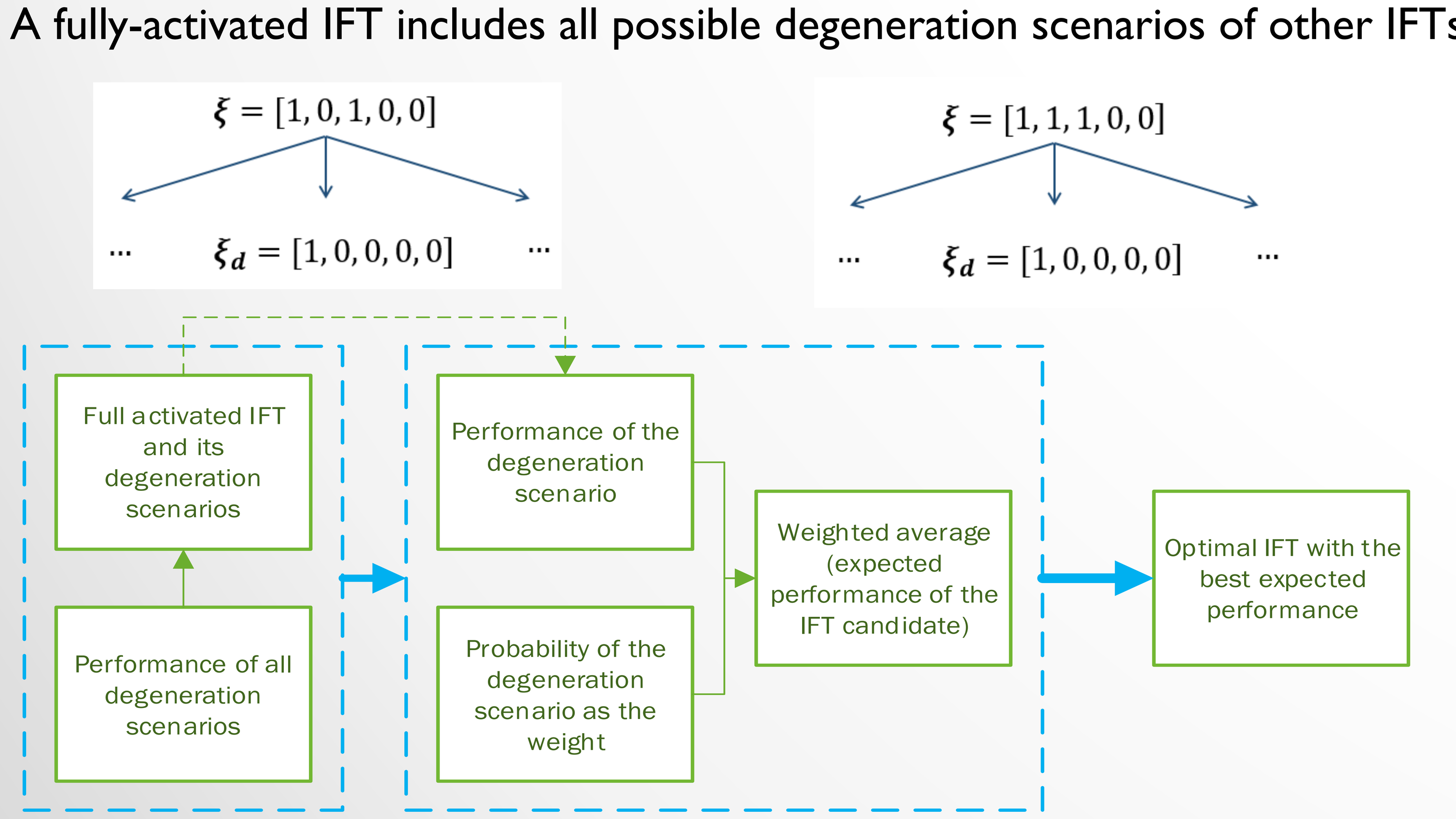
$$\min_{\xi\in\boldsymbol{\Omega}} 4\pi^2 \sum_{\xi_d(\xi)\in\boldsymbol{\Omega}_d(\xi)}\left[\prod_{i\in\boldsymbol{A_d}(\xi)} p_{i,\mathrm{unsat}} \sum_{i\in\boldsymbol{B_d}(\xi)}(1-p_{i,\mathrm{unsat}})\sum_{i=1}^{N}\int_0^{+\infty}\omega^2\mathrm{SS}_{X,i}^2(j\omega,\xi_{\boldsymbol{d}}(\xi))X_0^2(j\omega)d\omega\right]$$

s.t.

$$\begin{aligned}
&\xi = [\eta_0, \eta_1, \dots, \eta_N], \eta_i \in \{0,1\} \text{ for } i = 0,1,\dots,N\\
&\boldsymbol{\Omega} = \{[\eta_0, \eta_1, \dots, \eta_N] | \eta_i \in \{0,1\} \text{ for } i = 0,1,\dots,N\}\\
&\xi \in \boldsymbol{\Omega}\\
&\xi_{\boldsymbol{d}}(\xi) = [\eta_{0,d}, \eta_{1,d}, \dots, \eta_{N,d}], \eta_{i,d} \in \{0,1\}, \eta_{i,d} \le \eta_i \text{ for } i = 0,1,\dots,N\\
&\boldsymbol{\Omega_d}(\xi) = \{[\eta_{0,d}, \eta_{1,d}, \dots, \eta_{N,d}] \mid \eta_{i,d} \in \{0,1\}, \eta_{i,d} \le \eta_i \text{ for } i = 0,1,\dots,N\}\\
&\textstyle\sum_{\xi_d(\xi)\in\boldsymbol{\Omega}_d(\xi)} P_d(\xi_{\boldsymbol{d}}) = 1, \text{ for any } \xi \in \boldsymbol{\Omega}\\
&\boldsymbol{A_d}(\xi_{\boldsymbol{d}}(\xi)) = \{i|\eta_i = 1, \eta_{i,d} = 1, i = 0,\dots,N\}\\
&\boldsymbol{B_d}(\xi_{\boldsymbol{d}}(\xi)) = \{i|\eta_i = 1, \eta_{i,d} = 0, i = 0,\dots,N\}
\end{aligned}$$

Two-step algorithm:

- A fully-activated IFT includes all possible degeneration scenarios of other IFTs.



- Performance table of degeneration scenarios for the fully-activated IFT;
- Traverse all possible degeneration scenarios, and add the corresponding control performances from the table generated in the first step with a weight formulated from the communication model to obtain the expected string stability of the IFT candidate.

5. Numerical Experiment

Experiment setups:

- The experiment setup consists of a N+1 CAV platoon with one leading vehicle (i=0) and N following vehicles (i=1,…,N, and N=11,…,15).
- The movement of the leading vehicle is predetermined according to NGSIM field data.

Objectives:

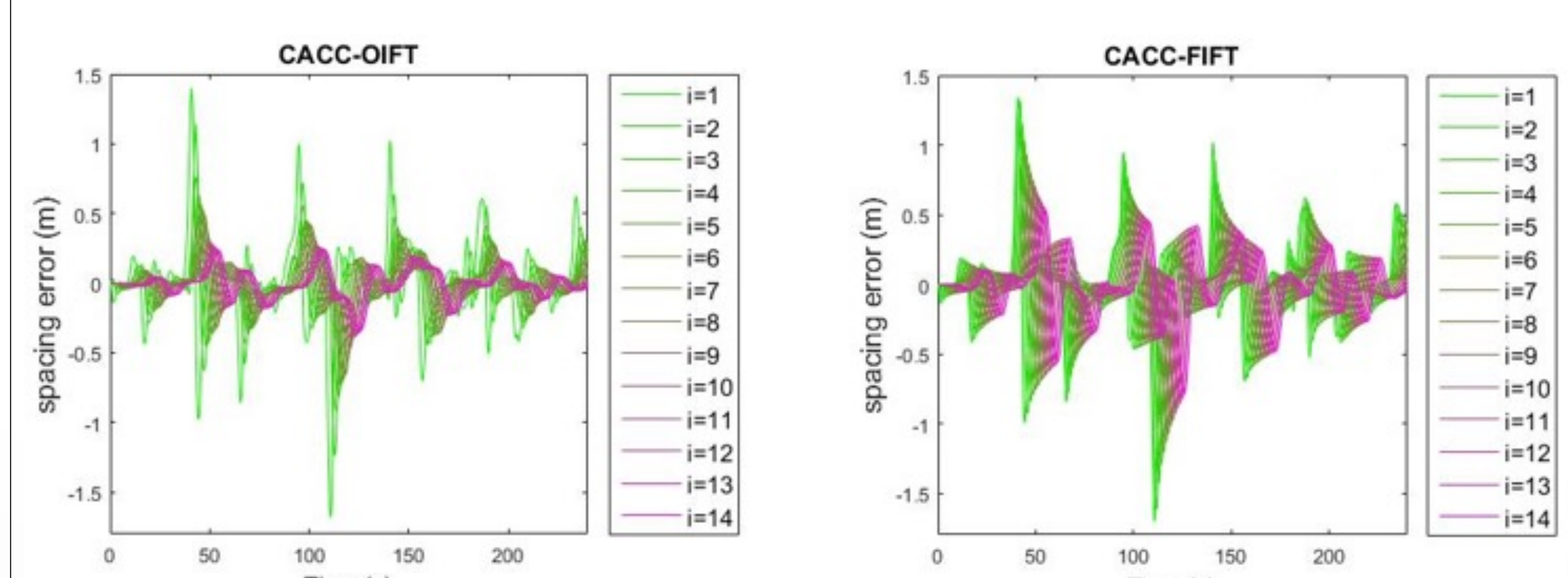
- Test the optimization result under different V2V communication scenarios.
- Compare CACC-OIFT with existing CACC-DIFT.
  - CACC-OIFT: CACC includes the IFT optimization
  - CACC-FIFT: control strategy includes the CACC and ACC schemes (*Naus et.al., 2010*) without IFT optimization

The optimization result under different V2V communication scenarios:

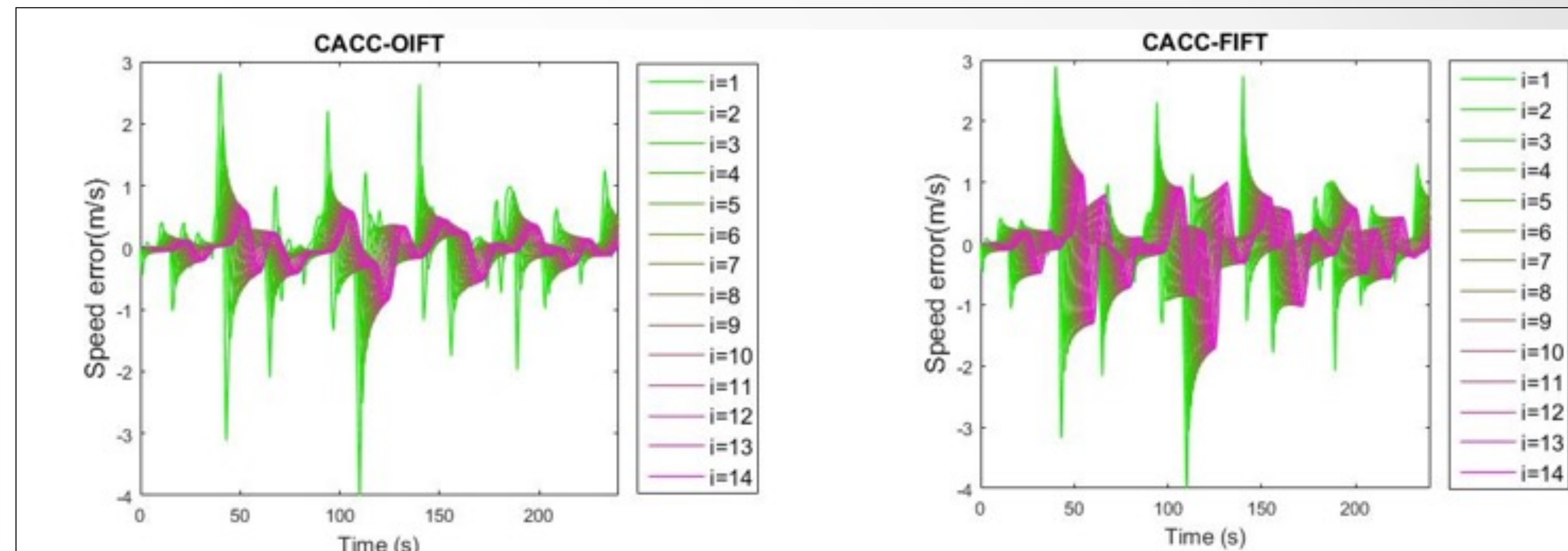
- The table illustrates the optimal IFTs under different ambient traffic densities $\bar{k}$ and platoon size N.
- Consecutive vehicles with activated "send' functionalities.
- Consecutive vehicles with deactivated "send" functionalities directly following those with activated ones.

N=14	Optimal IFT	$\bar{k}$=25	Optimal IFT
$\bar{k}$=25	111100011100000	N=11	111100011100
$\bar{k}$=30	111100001110000	N=12	1111000111000
$\bar{k}$=35	111100000111000	N=13	11110001110000
$\bar{k}$=40	111100000011100	N=14	111100011100000
		N=15	1111000111000100

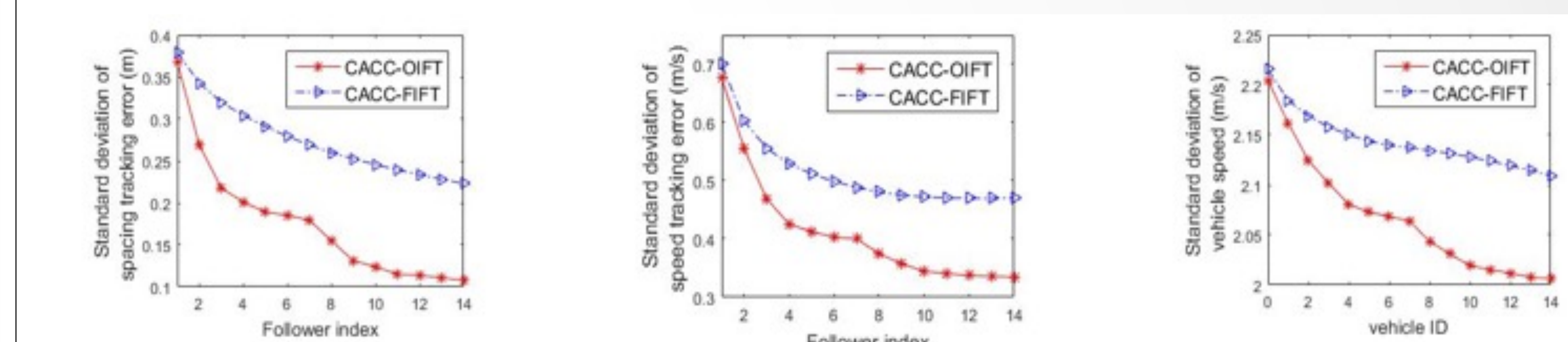
Performance comparison between CACC-OIFT and CACC-DIFT



(a) Spacing tracking error of CACC-OIFT (b) Spacing tracking error of CACC-FIFT



(c) Speed tracking error of CACC-OIFT (d) Speed tracking error of CACC-FIFT



(a) Standard deviation of spacing tracking error (b) Standard deviation of speed tracking error (c) Standard deviation of vehicle speed

- To compare the performance of CACC-OIFT with those of CACC-FIFT, a 15-CAV platoon is analyzed in a traffic flow with average density 28.57 vehicle/km for 240s. Under CACC-OIFT, the vehicle platoon will follow the IFT from the optimization model (111100011100000).
- Fig. (a) and (b) illustrates that the spacing tracking error of vehicles is mitigated based on their positions in the platoon. The figure shows that CACC-OIFT outperforms CACC-FIFT.
- The standard deviation of spacing tracking error decreases sequentially across vehicles in the platoon for both controllers. However, the spacing error of CACC-OIFT reduces the more quickly.
- The fluctuation in standard deviation of speed decreases under all three schemes as the tail of the platoon is approached, which implies that traffic oscillations are damped.

6. Summary

- This study proposes a novel CACC strategy, CACC-OIFT, to explicitly factor IFT dynamics and to leverage it to enhance the platoon performance in an unreliable V2V communication context for a pure CAV platoon.
- Contributions:
  - The IFT optimization model determines the optimal IFT that dynamically activates and deactivates the "send" functionality of the V2V communication devices of all vehicles in platoon.
  - The degeneration scenario probabilities are determined based on the communication failure probabilities for that time period which depend on the ambient traffic conditions.
  - The speed oscillation energy in frequency domain is used to evaluate the platoon control performance for a given IFT degeneration scenario.
  - In the operational deployment context, the adaptive controller continuously determines the car-following behaviors of the vehicles in the platoon.