Security of Distributed Cyber-Physical Systems with Connected Vehicle Applications

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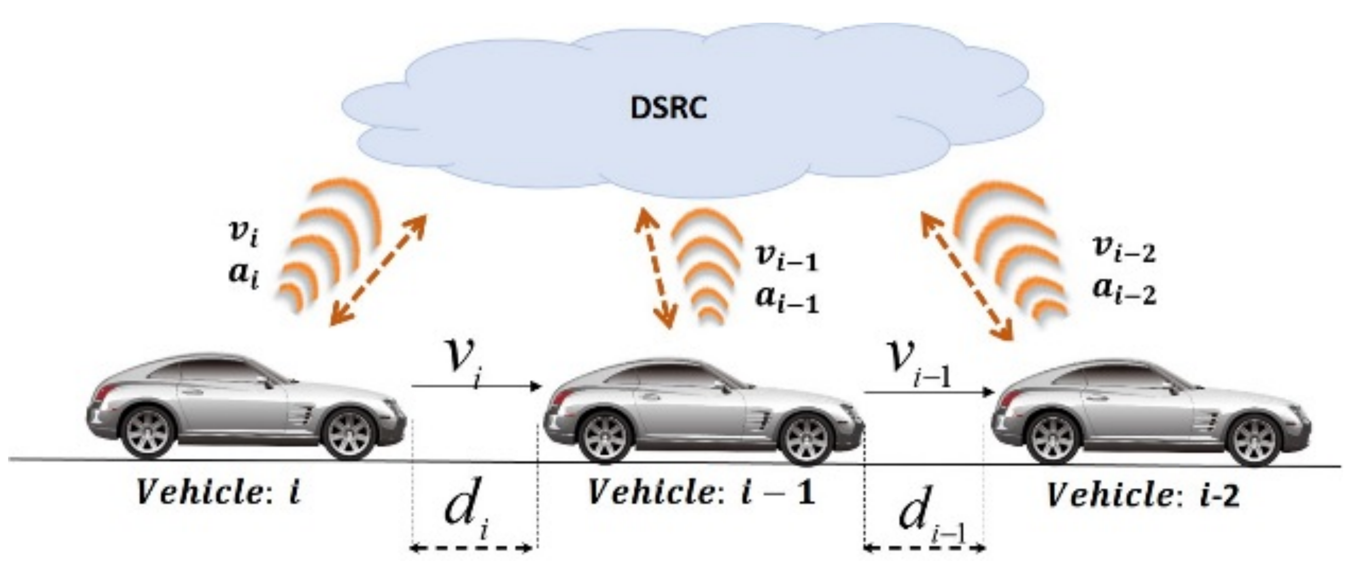
Background

Self-driving cars are no longer science fiction. Applications, such as collision avoidance and platooning, suggest interactions between multiple vehicles that are not owned and maintained by one entity. However, wireless interactions are vulnerable to cyber attacks. What strategic plan can be applied to secure smart cars?



Motivation

- Increasing the security of vehicles
- Increasing the traffic throughput
- Reducing fuel consumption and emission
- Reducing the human failure and accident

Problem Statement

$$\begin{cases} \dot{X}_i = A_i X_i + \sum_{j \neq i} K_{ij} X_j + B_i U_{ext} \\ Y_i = C_i X_i \end{cases}$$

Under Attack

$$\Gamma_1: \quad \underline{X}_i(t) = \chi(t).X_i(t), \quad \chi(t) \in \{0,1\}$$

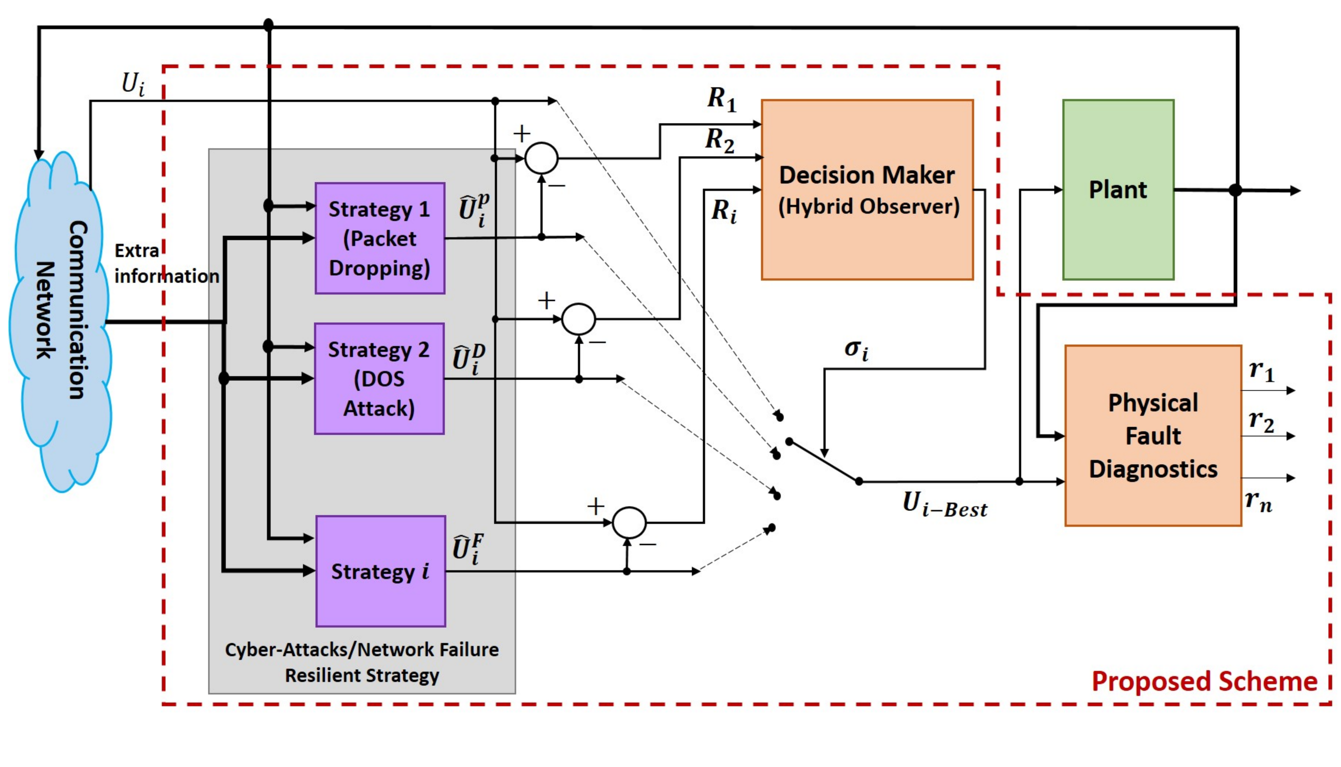
$$\Gamma_2: \quad \underline{X}_i(t) = X_i(t-\tau) \quad ,\tau \in \{\tau_i \mid \tau_{\min} < \tau_i < \tau_{\max}\}$$

$$\Gamma_K: \quad \underline{X}_i(t) = X_i(t) + \delta_i(t) \quad ,|\delta_i(t)| < M(t) < \min(X_i(t))$$

Hybrid Observer

Vehicle is not compromised, however, the attack exist in the communication network

Strategy:
Detect cyber-attacks and design controller to counteract the attack for each cyber-attack

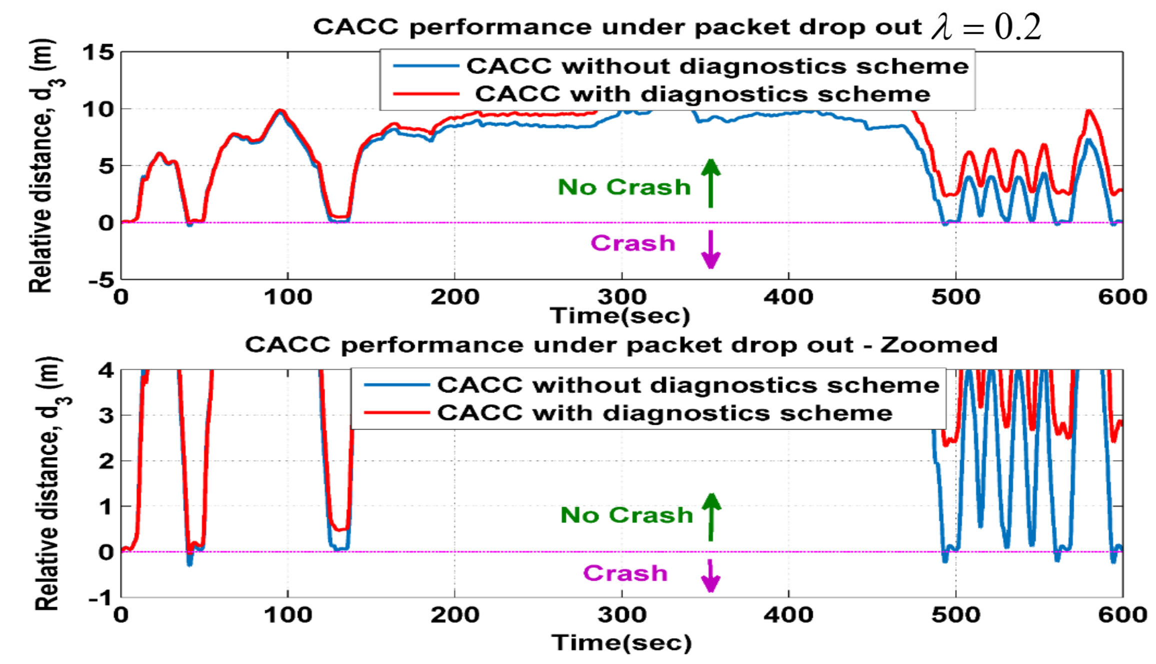


Packet Dropping

$$\begin{bmatrix} \dot{d}_i \\ \dot{v}_i \\ \dot{a}_i \end{bmatrix} = \begin{bmatrix} 0 & -1 & 0 \\ 0 & 0 & 1 \\ \frac{k_p}{h} & -\left(k_p + \frac{k_d}{h}\right) & -\left(k_p + \frac{1}{h}\right) \end{bmatrix} \begin{bmatrix} d_{im} \\ v_{im} \\ a_i \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \\ \frac{k_d}{h} \end{bmatrix} v_{i-1} + \begin{bmatrix} 0 \\ 0 \\ \frac{1}{h} \end{bmatrix} a_{i-1}$$

$$i \in S_m \setminus \{1\}$$

$$\dot{u}_i = -\frac{1}{h}u_i + \frac{1}{h}(k_p e_i + k_d \dot{e}_i) + \frac{1}{h} \times \psi(k) \times u_{i-1} \qquad \begin{cases} p(\psi(k)=0) = \lambda \\ p(\psi(k)=1) = 1-\lambda \end{cases}$$

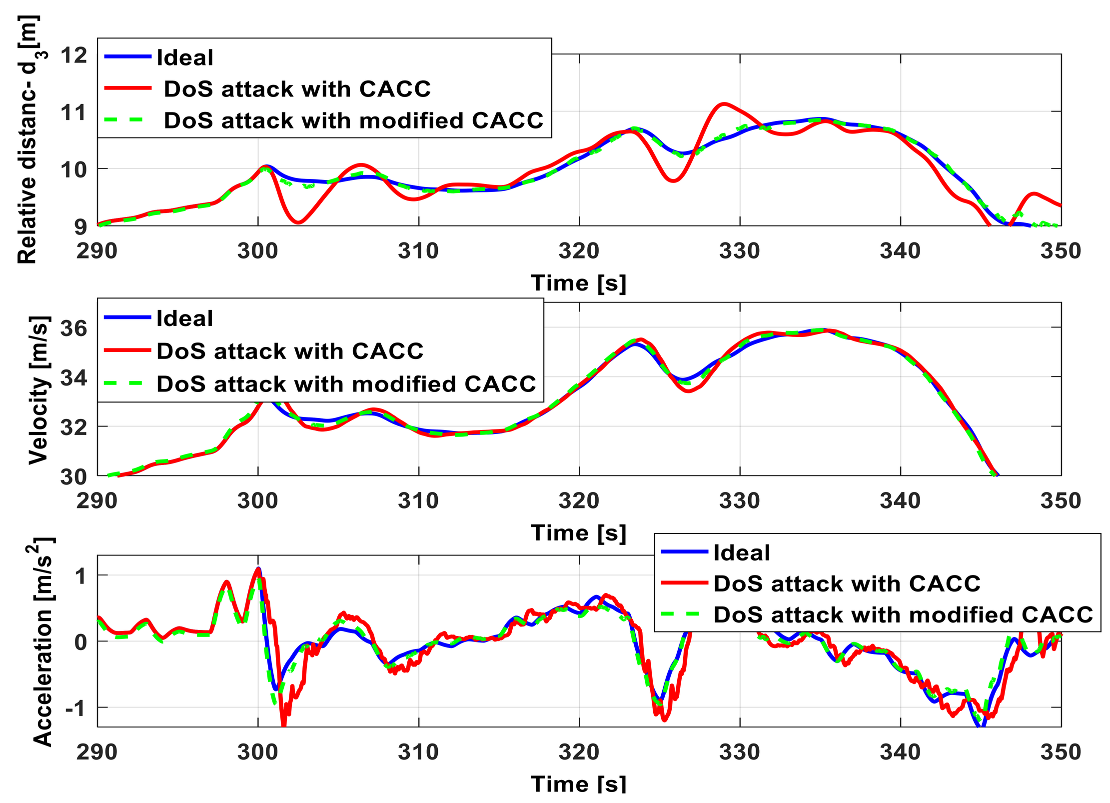


Results for Denial of Service (DoS) Attack

$$\begin{bmatrix} \dot{d}_i \\ \dot{v}_i \\ \dot{a}_i \end{bmatrix} = \begin{bmatrix} 0 & -1 & 0 \\ 0 & 0 & 1 \\ \frac{k_p}{h} & -\left(k_p + \frac{k_d}{h}\right) & -\left(k_p + \frac{1}{h}\right) \end{bmatrix} \begin{bmatrix} d_{im} \\ v_{im} \\ a_i \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \\ \frac{k_d}{h} \end{bmatrix} v_{i-1} + \begin{bmatrix} 0 \\ 0 \\ \frac{1}{h} \end{bmatrix} a_{i-1}(t-\tau)$$

$$i \in S_m \setminus \{1\} \qquad \tau_{\min} < \tau < \tau_{\max}$$

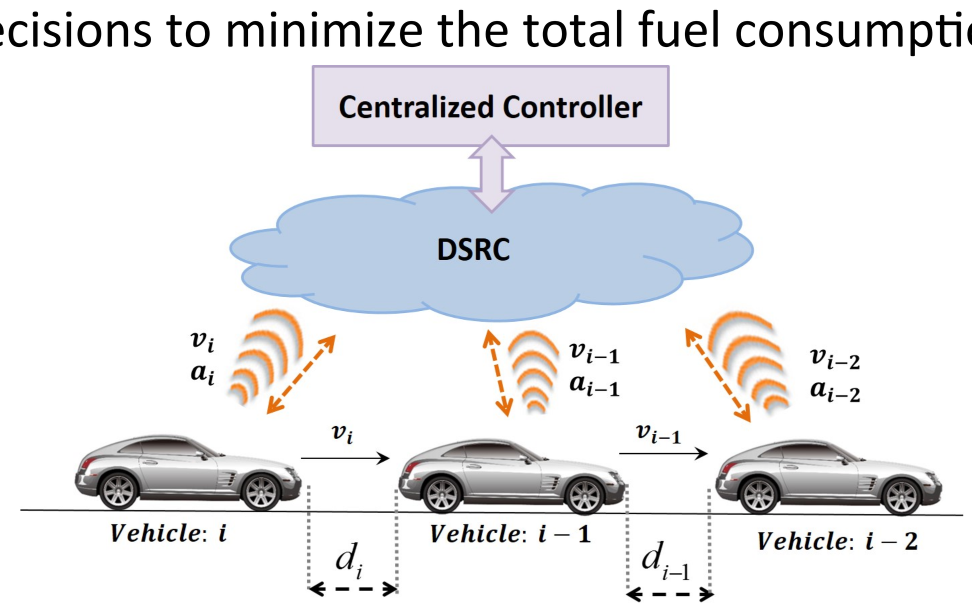
τ: Communication delay due to DoS attack



Platooning System Models

Strategy:

(1) Centralized Control: All vehicles send information to a centralized controller, who makes the optimal decisions to minimize the total fuel consumption.



(2) Decentralized Control: Each vehicle makes its own decision based on local information to minimize its own fuel consumption.

Fuel Optimization Problem

One-step cost function

$$L_i\left(v_i(t), s_i(t), a_i(t), d_i(t), v_{i+1}(t)\right) = \omega_1 \frac{Fuel}{v_i(t)} + \omega_2 R_{error}^2 + \omega_3\left(v_i(t) - V_d\right)^2 + \omega_4 a_i(t)^2 + \omega_5\left(v_{i+1}(t) - V_d\right)^2$$

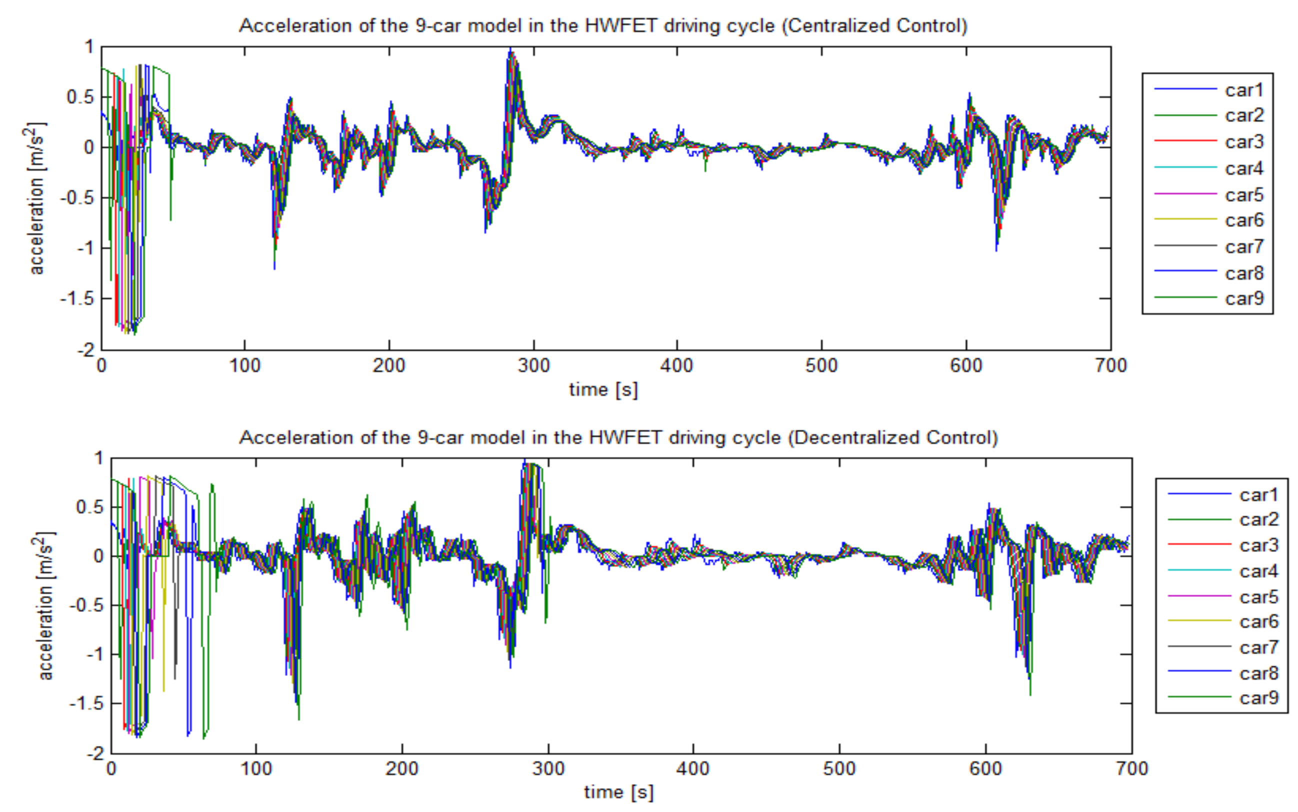
Fuel Consumption

$$Fuel = b_0 + b_1 v_i(t) + b_2 v_i(t)^2 + b_3 v_i(t)^3 + \hat{a}\left(c_0 + c_1 v_i(t) + c_2 v_i(t)^2\right)$$

Acceleration

$$\hat{a} = -\frac{1}{2M}\Phi\left(d_i(t)\right) C_D \rho_a A_\upsilon v_i(t)^2 - \mu g \cos\theta\left(s_i(t)\right) + a_i(t)$$

Acceleration Results



Fuel Consumption Results

Centralized Control Fuel Consumption (gallon/hour)

Number of cars in the platooning system	3	5	7	9
Fuel Consumption Average	5.764	5.763	5.763	5.764
Fuel Consumption Variance	0.34	0.39	0.14	0.20
Fuel Saving Percentage*	4.74%	4.74%	4.74%	4.73%

Decentralized Control Fuel Consumption (gallon/hour)

Number of cars in the platooning system	3	5	7	9
Fuel Consumption Average	5.763	5.762	5.761	5.761
Fuel Consumption Variance	0.72	1.55	1.69	1.37
Fuel Saving Percentage*	4.74%	4.77%	4.78%	4.78%

*Fuel saving percentage is calculated by comparing with fuel consumption without platooning.

Benefits

Scientific Impacts

- Potential improvement in traffic conditions, vehicle and personal safety, and energy consumption
- Collision avoidance
- More security is valuable for car makers and auto insurances

Broader Impacts

- General approach for distributed networked CPSs
- This method makes CPSs more resilient and secure to cyber attacks
- Research data is useful for public and private agencies responsible for providing infrastructure side of the connected vehicle system

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