A Micro-Simulation Study of Connected Vehicle Data-Aided Ramp Metering Facing Cyber Disruptions

Yu Tang[a], Jingqin Gao[a], Kaan Ozbay[a], Li Jin[b]
[a]New York University, [b]Shanghai Jiao Tong University

C2SMARTER CONNECTED COMMUNITIES WITH SMART MOBILITY TO EQUITABLY REDUCE CONGESTION

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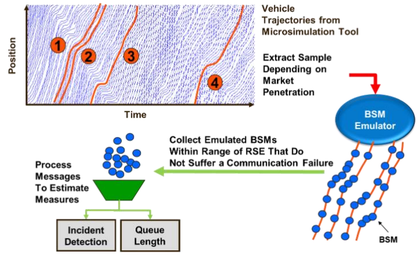
Abstract

Connected vehicles (CVs) can yield substantial informative data, such as basic safety messages (BSMs), during vehicle-to-vehicle or vehicle-to-infrastructure communications. One can apply these data to enhance current traffic control strategies. However, cyber disruptions, such as packet loss, are prevalent in cyber- physical systems and they could compromise these deliberately designed control methods. Currently, limited study evaluates traffic control facing cyber disruptions. In this paper, we investigate in a micro-simulation way how CV data-aided ramp metering, one kind of traffic control widely used in freeway management, is compromised by packet loss. To this end, we first utilize a BSM emulator to generate BSMs from CV trajectory, during which we take into account packet loss in communication between vehicles and road-side units. Then the corrupted BSMs is fed to a data convertor so that we obtain aggregated CV measurements required by state estimators and ramp controllers. Our micro-simulation study finds that that the robust closed-loop estimator could achieve better performance than open-loop estimator given low intensity of packet loss. But when packet loss occurs frequently, even the robust closed-loop estimator could achieve poor performance. This result implies that it is necessary to secure traffic control facing intense cyber disruptions.

Motivations

- **Fine-grained data available in a connected vehicle environment**
  - E.g. basic safety messages including vehicle-level speed, position, and so on.
  - Facilitate real-time traffic state estimation and control.

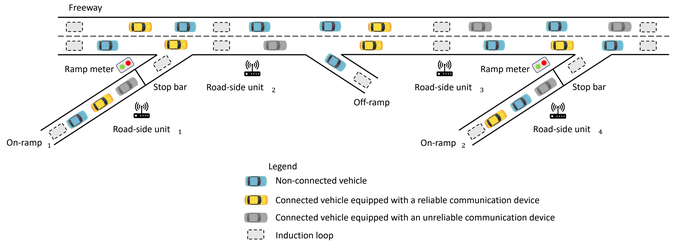


- **Cyber failures could occur during vehicle-to-vehicle or vehicle-to-infrastructure communications, which may degrade both estimation and control based on CV data.**
  - Reliability-related cyber disruptions: communication delay, packet loss, and so on.
  - Security-related cyber attacks: false data injection, denial-of-service attack and so on.

Problem Settings

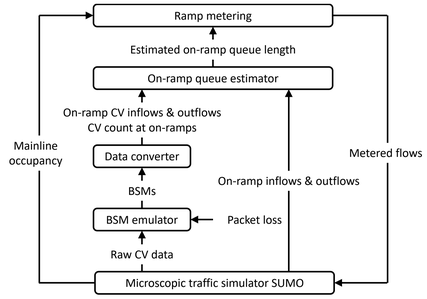
- **We investigate in a micro-simulation way how CV data-aided ramp metering is compromised by packet loss.**
  - CV data-aided ramp metering relies on the ramp queue length estimator that combines conventional sensors and emerging CV data.
  - Ramp metering algorithms have been developed, with the assumption of available measurements of on-ramp queue length. However, ramp queue length is not easily estimated from traditional traffic sensors, e.g. induction loops.

- **Freeway corridor with access control**
  - Mixed traffic environment where only partial vehicles are CVs.
  - Road-side units are deployed to collect CV data; packet losses occur during vehicle-to-infrastructure communications.



Simulation Framework

- **SUMO-based simulation framework**
  - Major components: i) BSM emulator, ii) on-ramp queue estimator and iii) ramp controller



- **BSM emulator**
  - The BSM emulator takes raw CV data as input and generates BSMs, including vehicle ID, position, speed, heading, break system status and vehicle size.

Algorithm 1 An algorithm generating BSMs from CV trajectory

```
Initialization unreliableDeviceList=[]
for t = 0, 1, ··· do
    for each vehicle v in the freeway system do
        if vehicle v enters the freeway system at time step t then
            add vehicle v to unreliableDeviceList with probability β
        end if
        if vehicle v in unreliableDeviceList then
            send its BSM to available RSUs with probability 1 − γ
        else
            send its BSM to available RSUs
        end if
    end for
end for
```

- **On-ramp queue length estimator**
  - Open-loop estimator

$$\hat{q}_{i,o}(k) = \frac{2\tilde{q}_i^{\mathrm{cv}}(k)}{\tilde{f}_{i,\mathrm{in}}^{\mathrm{cv}}(k)/\tilde{f}_{i,\mathrm{in}}(k) + \tilde{f}_{i,\mathrm{out}}^{\mathrm{cv}}(k)/\tilde{f}_{i,\mathrm{out}}(k)}$$

  - Close-loop estimator*

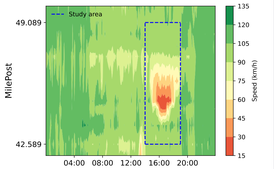
$$\begin{bmatrix}\hat{q}_{i,r}(k+1)\\ \hat{q}_{i,r}^{\mathrm{cv}}(k+1)\end{bmatrix} = \begin{bmatrix}1 & 0\\ \alpha & 0\end{bmatrix}\begin{bmatrix}\hat{q}_{i,r}(k)\\ \hat{q}_{i,r}^{\mathrm{cv}}(k)\end{bmatrix} + T_c\delta_t\begin{bmatrix}\tilde{f}_{i,\mathrm{in}}(k)\\ \tilde{f}_{i,\mathrm{in}}^{\mathrm{cv}}(k)\end{bmatrix} - T_c\delta_t\begin{bmatrix}\tilde{f}_{i,\mathrm{out}}(k)\\ \tilde{f}_{i,\mathrm{out}}^{\mathrm{cv}}(k)\end{bmatrix} + L(\tilde{q}_i^{\mathrm{cv}}(k) - \hat{q}_{i,r}^{\mathrm{cv}}(k))$$

(* Yu Tang, Kaan Ozbay, Li Jin. Robust Queue Length Estimation for Ramp Metering in a Connected Vehicle Environment. Presented at IEEE International Conference on Intelligent Transportation Systems, 2023)

- **Ramp metering algorithm**
  - ALINEA adopted for fair comparison of accuracy of queue length estimation
  - X-ALINEA/Q adopted for comparison of control performance given queue length estimation

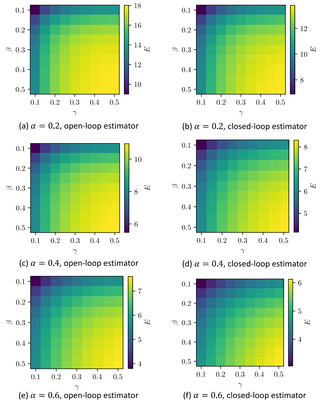
Simulation Results

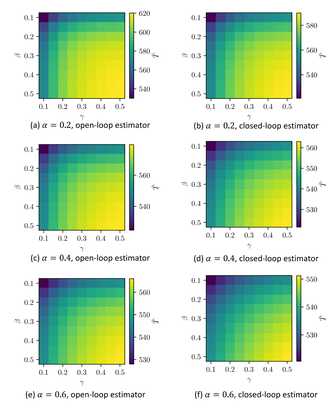
- **Study area**
  - A section of Interstate 210 Eastbound in Los Angeles, California



- **Performance comparison**

Estimation comparison (estimation error) | Control comparison (Total travel time per vehicle)





- **Findings**
  - The robust closed-loop estimator could achieve better performance than open-loop estimator given low intensity of packet loss.
  - When packet loss occurs frequently, even the robust closed-loop estimator could achieve poor performance. It indicates necessity of securing traffic control facing intense cyber disruptions.

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