Mitigating Highway Bottleneck Congestion by Leveraging Multi-Agent Reinforcement Learning and Connected and Autonomous Vehicle Capabilities

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Introduction

Active traffic management (ATM):
- Practical strategy to mitigate congestion and assuage traffic flow problems

Traditional ATMs often require driver compliance
  - E.g., speed harmonization

Connected and Autonomous Vehicles (CAVs) can be used as a tool for active traffic management without explicit driver compliance

Methodology

Combines reinforcement learning (RL) and graphical neural networks (GNN)

Model Structure:
- Fully Connected Network (FCN) encoder, \( \varphi \)
- Graph Convolution Network (GCN) layer
- Deep Deterministic Policy Gradient (actor + critic network)

- FCN encoder takes raw information \( X_t \) to generate node embeddings \( H_t = \varphi(X_t) \in \mathcal{H} \)
- GCN layer computes embeddings as
  \[
  Z_t = g(H_t, A_t) = \sigma(D_t^{-1/2} A_t D_t^{-1/2} H_t W + b)
  \]
- Actor network outputs individual vehicle acceleration directly from \( Z_t \)
- Action Space:
  \[ \mathcal{A} = \{a_1\}_{t=1}^{T}, \text{ where } a_t \in [-3 \text{ m/s}^2, 3 \text{ m/s}^2] \]
- State Space:
  Node features \( X_t \), comprised of vehicle position and velocity
  Adjacency matrix \( A_t \in \mathbb{R}^{N \times N} \)
- Reward:
  Penalty for high speed standard deviations
  Reward for outflows
  \[
  R = r_1 + r_2 = 3600 \sum_{i=1}^{T} \frac{\text{Max SSD}}{T} - \frac{\beta \mu^2}{n_p}
  \]

Experiment Setup

Simulation using open-source traffic simulator SUMO combined with FLOW
Moderately congested network:
- 0.5-km segment with 4-lanes
- Lane drop to 3-lanes at 0.3-km
- Lane drop to 2-lanes at 0.4-km
- Inflow of 1500 vehicles/hr
- CAV share of traffic stream at 10%

Severely congested network:
- 1.0-km segment with 4-lanes
- Lane drop to 2-lanes at 0.6-km
- Lane drop to 1-lane at 0.8-km
- Inflow of 2300 vehicles/hr
- CAV share of traffic stream at 8%

Training results are compared with baseline, rule-based control using the Intelligent Driver Model with LC2013 lane changing behavior

Results

- In both the moderately congested and severely congested scenarios, the use of CAVs to mitigate bottleneck congestion is more successful than a rule-based, car following behavior.
- This can be observed in Figure 6, which shows the outflows under the RL model is superior to the rule-based model.

Conclusions

- Based on the results of the simulation, it is highly feasible to use CAVs to actively manage traffic to mitigate bottleneck congestion.
- Of particular significance is the realization of this objective without explicit human driver cooperation.
- Following this study, future work can be conducted to include varying degrees of lane occupancy control as well as acceleration control of CAVs, which may be more effective in mitigating highway bottleneck congestion.