Introduction

Based on Connected Vehicle (CV) technology, a number of Eco-Approach and Departure (EAD) applications have been designed to guide vehicles to travel through signalized intersections in an eco-friendly way, avoiding unnecessary idling and minimizing acceleration/deceleration events. Most of the existing EAD applications were developed and tested in traffic-free scenarios or in a fully connected environment where presence and behavior of surrounding vehicles are detectable and predictable. The authors' previous studies improved the existing EAD algorithm in the terms of developing a short-term vehicle speed predictor which computes the optimal trajectory under the constraints from the preceding vehicle's movement. However, the effectiveness of EAD application is impacted by not only preceding vehicles' dynamic state but also the preceding traffic condition at the intersection. To this end, it is essential to embed accurate and efficient estimation of the queue length and dispersion time in real time into EAD algorithms.

In this research, we propose a queue forecasting based EAD algorithm (QF-EAD) to provide an optimal vehicle trajectory considering proceeding queue length and vehicle movement in a mixed traffic condition. A real-time estimation model for the queue length is developed using multi-source sensor data, including the GPS trajectories from CVs via vehicle to vehicle (V2V) communication, travel time data from fixed location sensor detection and preceding vehicle dynamic data from radar detection. A two-layer approach is proposed for accurate and efficient estimation of the queue and travel time information based on both sample vehicle trajectory from CVs and vehicle passage time from fixed location sensors. The first layer is estimation of the number of vehicles in queue at intersections based on the traffic data collected from loop detectors. The second layer is information integration on the first layer estimation with the probe vehicle trajectories from connected vehicle technologies. Based on signal phase and timing (SPAT), predicted location and time of preceding vehicle movement within the queue as well as queue length, the queue forecasting EAD algorithm is applied to design a smoothed trajectory that minimizing the fuel consumption and emissions considering the proceeding traffic and queues at intersection. Numerical experiments are conducted using Peachtree data from Next Generation Simulation dataset, with promising results.

Queue forecasting model

Queue length and delay play a primary role in determining the arterial performance. Besides, the queue propagation also have effect on the behavior of the preceding vehicle specially when it’s going to join the queue (see Figure 1). The number of vehicles joining the queue during the cycle is estimated given the lane-specific loop detector actuations and SPaT. The queue disperse rate and between vehicles spacing were calibrated based on Lighthill-Widnam-Richards (UWR) model. Given the vehicle speed and timing collected by loop detector, we are able to accurately estimate the vehicles within the queue as well as their joining location and timing. We consider the slowly moving vehicles (whose speed below 5 km/h) joining the rear end of the queue as part of the queue. The left turn and right turn movement are considered in the queue length estimation for each lane to improve the estimation accuracy. The estimation results obtained were validated using actual value that are extracted by post processing. Mean Absolute Percentage Error (MAPE) is the measurement for accuracy which is calculated by

\[
MAPE = \frac{100}{N} \sum_{i=1}^{N} \left| \frac{\text{Observed} - \text{Estimated}}{\text{Observed}} \right|
\]

Figure 2 shows the queue forecasting results for each lane based only on loop detector, respectively. MAPE for queue location in lane 1 is 17.6% and timing is 8.8%, MAPE for queue location in lane 2 is 15.8% and timing is 1.4%. The accuracy for the estimation will be further improved after we incorporates the probe vehicle data from connected vehicle technology.

Queue forecasting-based EAD system architecture

Figure 2. Results of forecasting the position and time vehicles joining the queue

Table 1 Performance of the Proposed QF-based EAD Algorithm

<table>
<thead>
<tr>
<th></th>
<th>HC (g/mile)</th>
<th>CO (g/mile)</th>
<th>NOx (g/mile)</th>
<th>CO2 (g/mile)</th>
<th>Energy (KJ/mile)</th>
<th>PM2.5 (mg/mile)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>0.49</td>
<td>8.2</td>
<td>1.23</td>
<td>773</td>
<td>10767</td>
<td>27.9</td>
</tr>
<tr>
<td>EAD without prediction</td>
<td>0.46</td>
<td>7.3</td>
<td>1.09</td>
<td>695</td>
<td>9716</td>
<td>24.1</td>
</tr>
<tr>
<td>EAD with prediction</td>
<td>0.41</td>
<td>6.7</td>
<td>0.84</td>
<td>658</td>
<td>9203</td>
<td>13.9</td>
</tr>
</tbody>
</table>

| Saving in % | 10.8 | 8.2 | 22.9 | 5.3 | 5.3 | 42.3 |

Figure 4. A comparison of different driving strategies.

Conclusions and Future Work

This research proposes a QF-based EAD system that enables the driver to travel through a signalized intersection in a safe and eco-friendly manner with interaction from other traffic and preceding queue.

The validation results indicate that the proposed queue forecasting model can predict the preceding vehicle’s location and time point within the preceding queue with reasonable accuracy in different lanes.

Based on SPAT and GID information as well as predicted states of preceding vehicle, the proposed QF-EAD algorithm can provide a smoother and more energy-efficient trajectory, compared to the EAD algorithm without prediction.

In the testing dataset, the QF-based EAD system is able to save 5.3% energy, and reduce 5.3%-42.3% air pollutant emissions compared to compared to EAD without prediction in congested traffic conditions.

The speed advisory system can be further upgraded into an automated, longitudinally-controlled system. Better system performance and environmental benefit are expected to achieve as the partial vehicle automation would diminish the negative impact of human factors (e.g., distraction).

Queue forecasting based EAD algorithm in urban arterials using multi-source sensor data
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