Eco-Cooperative Adaptive Cruise Control at Signalized Intersections: A Multiple Signal Optimization Approaches

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Abstract
Consecutive traffic signals produce continuous vehicle stops and accelerations on arterial roads and increase fuel consumption levels significantly. Eco-cooperative Adaptive Cruise Control (Eco-CACC) systems are one method to improve energy efficiency with the help of connected vehicle (CV) technology. In this paper, an Eco-CACC system is proposed to compute a fuel-optimized vehicle trajectory while traversing more than one signalized intersection. The proposed system utilizes Signal Phasing and Timing (SPaT) data and real-time vehicle dynamics to compute the optimum vehicle trajectory for connected CVs when approaching intersections. A comprehensive sensitivity analysis of a set of variables, including market penetration rates (MPRs), demand levels, phase splits, offsets, and distances between intersections, were tested using the INTEGRATION microscopic simulator to assess the benefits of the proposed algorithm. The analysis shows that, at 100% equipped-vehicle MPR, fuel consumption can be reduced by as much as 13.8%. Moreover, the results demonstrate that, as the MPR increases and phase splits decrease, larger savings in the overall fuel consumption levels are achievable, and there exist optimal values of the demand and the distance between the intersections to maximize the effectiveness of the algorithm. In addition, the study demonstrates that the algorithm works less efficiently when the signal offset is closer to its optimal value. The algorithm requires further enhancement to deal with over-saturated networks.

Motivation
- The major cause of high emissions and fuel consumption from vehicles on arterial roads has been widely related to frequent accelerations associated with stop-and-go waves at signalized intersections.
- The acceleration/deceleration events of vehicles on arterial roads are determined by the traffic signal settings and vehicle queues at multiple intersections.
- CV technology enables vehicles to exchange road traffic information, to communicate with signals to receive SPaT information, and to minimize their corresponding fuel consumption levels.
- A previous study of eco-driving on arterial corridors attempted to smooth acceleration/deceleration maneuvers of vehicles at isolated intersections.

Our Work
- Develop an Eco-CACC-MS algorithm with the consideration of vehicle queues to minimized fuel consumption levels at multiple intersections, and evaluate its benefits with the INTEGRATION traffic simulation model.
- Perform a sensitivity analysis of MPR of equipped vehicles, phase splits, offsets, distance between intersections, and demand levels.

Sensitivity Analysis
- Investigate the impacts of demand levels, offsets, and the distance between intersections.
- Two consecutive intersections with single-lane approaches and only through traffic were simulated to study various factors affecting the performance of algorithm.

Demand levels
- Positive savings in fuel consumption can be observed for all demand levels.
- With the Eco-CACC-MS-Q algorithm, the demand at 400 vphpl results in the best savings for the network.
- With the Eco-CACC-Q algorithm, the demands from 400 vphpl to 700 vphpl result in savings of 7%
- The savings are a result of the increase in the number of equipped vehicles in the network.

Offsets
- When the offset is closer to the optimal value, the fuel consumption savings obtained from both algorithms are smaller.
- At the optimal offset, most vehicles only need to stop at the first signal, which results in the least savings for both algorithms.
- The highest fuel consumption savings can be observed at 13.0% with 100-s offset for Eco-CACC-MS-Q, and 7.3% with 65-s offset for Eco-CACC-Q.

Distance between intersections
- There exists an optimal distance between intersections for both algorithms to maximize the savings in fuel consumption.
- When the distance is large enough, the two intersections can considered to be isolated to each other.

Significance Analysis
- All parameters have significant impact on the savings of fuel consumption;
- There are significantly larger savings from Eco-CACC-MS than those with only the consideration of a single signal.

\begin{table} 
| Term          | Estimate | Std Error | t Ratio | Prob>|t| |
|---------------|----------|-----------|---------|-----|
| Intercept     | 1.24     | 0.25      | 5.00\textsuperscript{*} <.0001* |
| Algorithm     | 0.59     | 0.037     | 15.76\textsuperscript{*} <.0001* |
| Number of lane| -1.10    | 0.075     | -14.79\textsuperscript{*} <.0001* |
| Demand levels | 0.0014   | 0.00024   | 5.39\textsuperscript{*} <.0001* |
| Offset        | 0.063    | 0.0017    | 37.36\textsuperscript{*} <.0001* |
| Signal Spacing| -0.0019  | 0.00026   | -7.02\textsuperscript{*} <.0001* |
| MPRs          | 0.061    | 0.0012    | 52.13\textsuperscript{*} <.0001* |
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