Eco approaching at an isolated signalized intersection under partially connected and automated vehicles environment

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\section*{Abstract}
This research proposed an eco-driving system for an isolated signalized intersection under partially Connected and Automated Vehicles (CAV) environment. This system prioritizes mobility before improving fuel efficiency and optimizes the entire traffic flow by optimizing speed profiles of the connected and automated vehicles. The optimal control problem was solved using Pontryagin's Minimum Principle. Simulation-based before and after evaluation of the proposed design was conducted. Fuel consumption benefits range from 2.02\% to 58.01\%. The CO2 emissions benefits range from 1.97\% to 33.26\%. Throughput benefits are up to 10.80\%. The variations are caused by the market penetration rate of connected and automated vehicles and v/c ratio. No adverse effect is observed. Detailed investigation reveals that benefits are significant as long as there is CAV and they grow with CAV's market penetration rate (MPR) until they level off at about 40\% MPR. This indicates that the proposed eco-driving system can be implemented with a low market penetration rate of connected and automated vehicles and could be implemented in a near future. The investigation also reveals that the proposed eco-driving system is able to smooth out the shock wave caused by signal controls and is robust over the impedance from conventional vehicles and randomness of traffic. The proposed system is fast in computation and has great potential for real-time implementation.

\section*{1. Introduction}
As reported by U.S. Environmental Protection Agency, the transportation sector is the second largest source of greenhouse gas (GHG) emissions and has contributed about 26\% of total U.S. GHG emissions in 2014 (\textit{Sources of Greenhouse Gas Emission, 2016}). Improving fuel efficiency and reducing emissions have become a critical focus of transportation research. Many approaches have been proposed accordingly, including advanced vehicle technology (Mendez and Thirouard, 2008), Eco Fuel (Durbin et al., 2011), traffic demand management (Strompen et al., 2012), advanced traffic signal control (Chen et al., 2011) and vehicle operation (Barth et al., 2011; Hu et al., 2016). Eco-driving is one important component of fuel efficiency improvement technologies (Barth et al., 2011; Xia et al., 2012). The main idea is to reduce acceleration, deceleration and idling by optimizing vehicle speed profile (Xia et al., 2013a,b; Li et al., 2014). Eco-driving can be categorized into:

\begin{itemize}
  \item Eco-driving
  \item Isolated signalized intersection
  \item Partially connected and automated vehicles environment
  \item Mobility
  \item Fuel efficiency
  \item Speed optimization
\end{itemize}
A number of eco-driving strategies on signalized arterials have been proposed. Some developed optimal controllers for individual vehicles, providing optimal speed profiles. Mandava and Barth designed a speed advisory system for human drivers traveling on signalized arterials under light traffic condition (Mandava et al., 2009). Later, Barth upgraded his speed advisory system with real-time capability (Barth et al., 2011; Xia et al., 2013a,b). Liu developed a more advanced controller that could consider the effect of front queue (He et al., 2015). Some others worked on providing ecological speed profiles for accelerating to desired speed when leaving an intersection (Xia et al., 2013a; Xia, 2014; Hao et al., 2015). Others studied to reduce the total fuel consumption and emissions by improving throughput (Zhou et al., 2017; Ma et al., in press; Lee and Park, 2012). Lee and Park removed signal with the help of Connected and Automated Vehicle (CAV) technology to improve throughput and reduce stops and deceleration delay which significantly brought down fuel consumption and emissions (Lee and Park, 2012). Li designed a control strategy based on shooting heuristic (SH) algorithm to pre-cluster vehicles into tight and fast marching platoons before passing an intersection in order to maximize throughput (Zhou et al., 2017; Ma et al., in press).

Non-connected vehicles can be "controlled" indirectly when they are following a connected vehicle. In this case, car-following model could be applied to establish "cooperation" between CAV and non-connected vehicles. Car-following model is a well-accepted concept that has been studied for years (Mehmood et al., 2003) and has been verified on arterials with field data (Ahn et al., 2004). For instance, it has been utilized to infer driver's intent at signalized intersection (Liebner et al., 2012), or used to analyze traffic oscillation under congestion (Li et al., 2014; Li and Ouyang). The concept of applying car-following model to indirectly "control" non-connected vehicles has also been confirmed valid in past studies. Kamal utilized the Gipps' car-following model to predict the state of the conventional vehicle to support the optimization of autonomous vehicle (Kamal et al., 2015). Wang used the Helly car-following model to construct a cooperative cruising system on freeway (Wang et al., 2014). Therefore, even in a partially CAV environment, a control system can be established.

The existing eco-driving systems have limitations. First, they are not suitable for congested signalized intersection (Barth et al., 2011; Xia et al., 2013a,b; Kamal et al., 2015; Rakha and Kamalanathsharma, 2011), because these eco-driving systems tend to slow vehicles down and thus have a negative impact on the throughput. As the result, although the fuel efficiency of the few CAVs are improved, the vast majority of the traffic is sacrificed. Second, they are not fit for real implementation in the current world. Most of them assumed that all vehicles are connected and automated vehicles which can take on the entire dynamic driving task (Zhou et al., 2017; Ma et al., in press; Lee and Park, 2012). Unfortunately, the market penetration of connected and automated vehicles will not reach one hundred percent until 2060 s (Alessandrini et al., 2015). Hence, the technologies developed based on complete connected and automated vehicles environment are not practical in a very long time.

Therefore, the objective of this research is to develop an optimal controller that is:

- functional in a partially connected and automated vehicles environment (feasible for real-world implementation in the near future)
- prioritizing mobility before improving fuel efficiency
- fast enough for potential real-time implementation
- applicable for isolated signalized intersection

The reminder of the paper is organized as follows: Section 2 'Control Structure' provides high-level descriptions and highlights of the control structure; Section 3 'Mathematical Formulation' presents problem formulation and the associated solution; Section 4 'Simulation Evaluation' describes simulation set-up and the associated results; Section 5 'Conclusion' entails the conclusions and future works.

2. Control structure

The goal of the proposed optimal controller is to improve fuel efficiency for vehicles approaching an isolated signalized intersection while causing no adverse effect to throughput. There are two highlights of this proposed controller:

- **Eco-driving with mobility priority:** The proposed controller provides the most ecological driving speed advisory while maintaining optimal mobility status for the intersection. The controller puts mobility (throughput) a higher priority than ecology. It enforces the CAV's final condition to optimize the mobility. The design ensures that all CAVs pass through the intersection with the smallest headway with their preceding vehicle and travel at legal speed limit. From a congregated perspective, the controller forces vehicles into tightest and fastest marching platoons at the stop line before optimizing vehicles fuel efficiency. Since flow rate equals to the product of density and speed, by maximizing density and speed, throughput at an intersection is optimized. Therefore, users of this proposed controller do not sacrifice travel time to save gasoline. It is a pure "win" control system.
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