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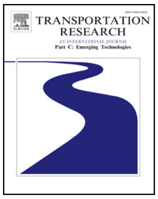

A platoon based cooperative eco-driving model for mixed automated and human-driven vehicles at a signalised intersection

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ABSTRACT

The advancements in communication and sensing technologies can be exploited to assist the drivers in making better decisions. In this paper, we consider the design of a real-time cooperative eco-driving strategy for a group of vehicles with mixed automated vehicles (AVs) and human-driven vehicles (HVs). The lead vehicles in the platoon can receive the signal phase and timing information via vehicle-to-infrastructure (V2I) communication and the traffic states of both the preceding vehicle and current platoon via vehicle-to-vehicle (V2V) communication. We propose a receding horizon model predictive control (MPC) method to minimise the fuel consumption for platoons and drive the platoons to pass the intersection on a green phase. The method is then extended to dynamic platoon splitting and merging rules for cooperation among AVs and HVs in response to the high variation in urban traffic flow. Extensive simulation tests are also conducted to demonstrate the performance of the model in various conditions in the mixed traffic flow and different penetration rates of AVs. Our model shows that the cooperation between AVs and HVs can further smooth out the trajectory of the latter and reduce the fuel consumption of the entire traffic system, especially for the low penetration of AVs. It is noteworthy that the proposed model does not compromise the traffic efficiency and the driving comfort while achieving the eco-driving strategy.

1. Introduction

Transportation is one of the main sources of energy consumption and greenhouse gas emission. In the EU, transportation is responsible for 33% of energy consumption and 23% of total emissions (European Commission, 2016). Road transport represents most of it, 72.8% in total greenhouse gas emissions and 73.4% in transport energy demand. A lot of work has been done to mitigate these effects from different aspects, for example, optimised engine design, better road surface condition and more training for drivers. Due to the continually increasing number of vehicles, however, the total vehicle fuel consumption is still rising. The concept of “eco-driving” has drawn increasing attention from both researchers and government (Carsten et al., 2016). The core of eco-driving technologies is to provide drivers with a variety of advice and feedback to minimise the fuel consumption and emissions while driving.

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Unlike continuous traffic flow on freeways, traffic flows on urban roads are regularly interrupted by traffic signals and conflicting traffic flows at intersections. As such, the vehicles travel with strong variations in their velocity and consume more fuel. Eco-driving strategies can be designed to reduce the idling time on the red light and subsequent strong acceleration by advising the drivers to approach intersections using a moderate acceleration and deceleration. The development of sensing and communication technologies make Vehicle-to-Infrastructure (V2I) and Vehicle-to-Vehicle (V2V) communication possible in the near future. These technologies offer potential applications for eco-driving patterns at intersections as the connected vehicles can receive the Signal Phase and Timing (SPaT) information from the intersection controller by V2I and also receive the position and velocity information from surrounding vehicles by V2V communication. Better speed advice can be generated using this information, and thus vehicles may adjust their speed in advance, in order to avoid stopping at the stop line and subsequent strong acceleration, and consequently reduce the fuel consumption.

Both field experiments (Schall and Mohnen, 2017) and simulator experiments (Van der Voort et al., 2001; Staubach et al., 2014) show that eco-driving reduces the fuel consumption between 5% and 18%, and drivers exhibit a high acceptance towards an eco-driving support system. It has no negative effects on safety, but many eco-driving methods lead to low travel speed and may have a negative impact on the following vehicles (Wu et al., 2015; Staubach et al., 2014). Moreover, they may even increase the travel time of the host vehicles and following vehicles.

This paper proposes a real-time cooperative eco-driving strategy for a platoon including mixed automated vehicles (AVs) and human-driven vehicles (HVs) approaching a signalised intersection. It adopts a model predictive control (MPC) method to control the trajectories of AVs. Here the AVs are considered the leaders of the platoon with the aim of minimising the total fuel consumption of the whole platoon without sacrificing the travel time of the leaders. It also reduces the travel time for the following vehicles to a certain extent. The rest of the paper is organised as follows: the literature review of the eco-driving modelling is presented in Section 2. Then, the proposed model structure, optimisation method, and platoon control scheme are described in Section 3. In Section 4, the properties of the proposed model are extensively studied and the performance of the proposed method for different penetration rates of AVs is also examined. A final Section 5 summarises the paper's findings.

2. Literature review

One of the applications of speed advisory systems is Intelligent Speed Adaptation (ISA) which is widely used in several EU countries (Almqvist et al., 1991; Liu and Tate, 2004). ISA devices are primarily aimed at safer driving by advising drivers a desired speed and speed limits on specific road sections (Ngoduy et al., 2009). Experiments showed that ISA strategies can potentially mitigate congestion and reduce fuel consumption and pollutant emissions due to smoother speed variations (Oei and Polak, 2002; Panis et al., 2006). In conventional ISA systems, vehicles are still driven by humans, and traffic information is usually obtained from loop detectors.

There are two main methods proposed in the literature which utilise the traffic signal information to reduce idle time and fuel consumption. The first approach suggests a constant speed or constant acceleration for an individual driver to reduce the idle time or fuel consumption. This is commonly named Green Light Optimised Speed Advisory (GLOSA) system. It is usually implemented as an optimisation model by assuming a simple speed pattern in front of the intersection. Rakha and Kamalanathsharma (2011) considered a fuel consumption model in the objective function and showed that simplified objective functions such as minimising the deceleration or idling time may not get the optimal result in terms of fuel consumption. This work is further extended to control the variable speed limit for each vehicle to minimise the fuel consumption (Kamalanathsharma et al., 2015) and integrate queue estimation (Yang et al., 2017). Mandava et al. (2009) developed an arterial velocity planning algorithm which provided speed advice to the drivers regarding the most fuel optimal path computed using upcoming signal information. The objective function was aimed at minimising the deceleration and acceleration rates, and 12–14% energy/emission savings were achieved. Tielert et al. (2010) conducted a large-scale simulation to identify the impact of gear choice and distance to the intersection. They found that sub-optimal gear choice can reduce the positive performance of the speed adaptation. Another finding was that the benefit of providing information to the vehicles located further than 600 m is negligible. Treiber and Kesting (2014) implemented three strategies of speed adaptation: early break, early start and avoiding queue in the Improved Intelligent-Driver Model. The travel time decreases linearly with the penetration of equipped vehicles. They also found that increasing the maximum speed from 50 km/h to 70 km/h doubles the performance index. Katwijk and Gabriel (2015) considered the impact of different trajectories on the fuel consumption. The vehicle was advised to use a smaller deceleration, even combined with a period of constant speed, instead of a hard deceleration in front of the red light. Stebbins et al. (2017) developed a method to suggest an acceleration to the leading vehicle only in a platoon to reduce delays. It was assumed that every vehicle that is the first to pass the intersection on a green light can be selected as a leading vehicle. Instead of controlling the speed directly, Ubiergo and Jin (2016) proposed a green driving strategy to control the individual advisory speed limit of connected vehicles while following their leaders at signalised intersections; it can be applied to any level of market penetration. Although no fuel consumption model was explicitly used in this modelling method, it still saved 15% in travel delays and 8% in fuel consumption and emission.

The second approach uses an optimal control or an MPC method to provide dynamic or real-time speed advice to an individual vehicle considering the local and predictive traffic states. This approach is thus more suitable for AVs because of the real-time detecting and speed adjustment. Asadi and Vahidi (2011) calculated the optimal speed that reduces idling at red lights using the given future state of traffic lights and developed an optimisation-based MPC model to consider multiple objectives. Kamal et al. (2013) predicted the dynamics of the preceding vehicle based on the information from inter-vehicle communication and considered the signal status of the upcoming intersections to compute the optimal vehicle control input for fuel economy by an MPC method. He