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Integrated vehicle and powertrain optimization for passenger vehicles with vehicle-infrastructure communication

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A B S T R A C T

This research proposes an optimal controller to improve fuel efficiency for a vehicle equipped with automatic transmission traveling on rolling terrain without the presence of a close preceding vehicle. Vehicle acceleration and transmission gear position are optimized simultaneously to achieve a better fuel efficiency. This research leverages the emerging Connected Vehicle technology and utilizes present and future information—such as real-time dynamic speed limit, vehicle speed, location and road topography—as optimization input. The optimal control is obtained using the Relaxed Pontryagin's Minimum Principle. The benefit of the proposed optimal controller is significant compared to the regular cruise control and other eco-drive systems. It varies with the hill length, grade, and the number of available gear positions. It ranges from an increased fuel saving of 18–28% for vehicles with four-speed transmission and 25–45% for vehicles with six-speed transmission. The computational time for the optimization is 1.0–2.1 s for the four-speed vehicle and 1.8–3.9 s for the six-speed vehicle, given a 50 s optimization time horizon and 0.1 s time step. The proposed controller can potentially be used in real-time.

1. Literature review

Transportation generates about 28% of greenhouse gas emissions in the United States (USDOT, 2015) and contributes 25% to the total energy consumption in developed countries (World Energy Council, 2015). It has caused concerns on sustainable energy supply and its environmental effect. Therefore, techniques that could improve vehicles' energy efficiency have become increasingly important.

Eco-driving is one of the many techniques that have been developed to improve vehicles' fuel efficiency (Suzdaleva and Nagy, 2014; Mohd Zulkefli et al., 2014, 2017; Pampel et al., 2015). It is, in nature, a vehicle controller taking advantage of Connected Vehicle (CV) data–which includes but not limited to traffic state (Wang et al., 2014a, 2014b), signal timing (Rakha and Kamalanathsharma, 2011), and terrain information (Hu et al., 2016; Schwarzkopf and Leipnik, 1977) – to have vehicles cooperate better with present and future conditions. Eco-driving considering terrain information has already been shown with sizable room for improvement. Past research demonstrated that a 6% increase in roadway grade leads to 40–94% increase in fuel consumption (Park and Rakha, 2006). Another study confirmed that the fuel economy on flat routes is superior to that on rolling or mountainous routes by approximately 15–20% (Boriboonsomsin and Barth, 2009). However, in theory, if no energy is wasted, vehicles traveling on rolling terrain should consume the same amount of fuel as vehicles on flat

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roads. The only difference is that the vehicles on rolling terrain constantly have energy transferring between potential energy and kinetic energy. Therefore, all the increases in fuel consumption observed in the past studies are unnecessary waste, which can be eliminated or reduced by optimizing vehicle state.

State-of-the-art eco-driving techniques can be advanced significantly. Past eco-driving systems mostly only consider vehicle speed trajectory optimization (Hooker, 1988; Mensing et al., 2012; Kamal et al., 2011; Wan et al., 2016). However, vehicle powertrain can also be optimized to improve engine working status to achieve real optimal fuel efficiency. Few studies have investigated integrated vehicle speed and powertrain optimization (Saerens and Van den Bulck, 2013; Hellström et al., 2010). However, their technologies are oversimplified and are not ready for real-world implementation for a multitude of reasons. First, their methods only considered constant slope scenario; thus the assumptions made to acquire optimal gear position do not hold for terrain with changing grade. Additionally, their methods do not allow vehicles to brake, which is necessary to exceed human comfort and safety requirement. Furthermore, their methods are computationally intensive and are not suitable for real-time applications.

The integrated optimization problem for regular vehicles involves a system with both continuous control input (engine torque) and discrete control input (gear position). This requires an innovative solution. The optimal gear position control trajectory is in the form of a sequence of discrete values that change at certain instances. To find this trajectory, several values must be determined: number of discrete input changes, time instances that discrete control changes and the sequence of the discrete input values.

Several methodologies have been identified in the literature, but are inappropriate or inadequate for this problem for various reasons. The Dynamical Programming (DP) approach (Hedlund and Rantzer, 1999; Borrelli et al., 2005) is computationally heavy, which prevents real-time implementation. Mixed Integer Programming (MIP) is another potential methodology with heavy computation (Bemporad and Morari, 1999; Sager, 2005). Its computational time increases exponentially as the number of discrete input point increases. A bi-level optimization framework (Xu and Antsaklis, 2002; Gonzalez et al., 2010) is also unsuitable because of its high computational intensity. Classical Pontryagin Minimum Principle (PMP), which was successfully used to solve a similar problem for hybrid vehicles (Hu et al., 2016), is only suitable for continuous systems; therefore, it is not appropriate for this problem. Extended PMP (EPMP) requires the sequence of the discrete control variable as known inputs in order to optimize time spent with each discrete control mode (Shaikh and Caines, 2007; Sussmann, 1999; Piccoli, 1998; Riedinger and Kratz, 2003). Since this sequence is unknown in the problem of interest, EPMP is not a suitable methodology for this problem. Ultimately, Relaxed Pontryagin's Minimum Principle (RPMP) is adopted in this paper for its capability of integrated optimization on both discrete and continuous variables and its low computing intensity (Bengea and DeCarlo, 2005).

In order to further advance the state-of-the-art of vehicle optimal controller for better fuel efficiency, the objective of this research is to develop a vehicle controller that

- Minimizes fuel consumption on rolling terrain for a regular gas-powered vehicle without the presence of a close preceding vehicle. The scenario is illustrated in Fig. 1.
- Solves vehicle level and powertrain level optimization simultaneously.
- Takes advantage of the Connected Vehicle technology.
- Reduces computational burden in preparation for future on-road applications.

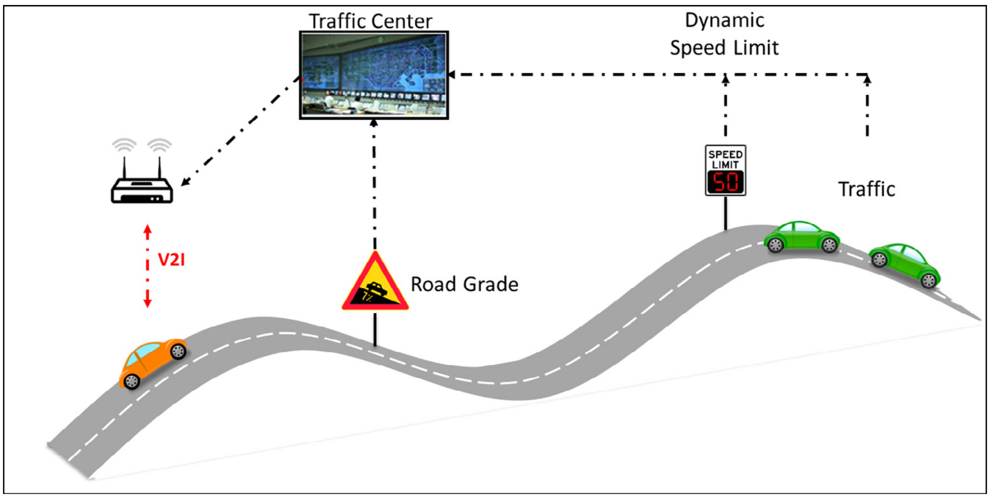

Fig. 1. Optimize fuel consumption using information from the vehicle-infrastructure communication.