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Hardware-in-the-loop testbed for evaluating connected vehicle applications

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ABSTRACT

Connected vehicle environment provides the groundwork of future road transportation. Researches in this area are gaining a lot of attention to improve not only traffic mobility and safety, but also vehicles' fuel consumption and emissions. Energy optimization methods that combine traffic information are proposed, but actual testing in the field proves to be rather challenging largely due to safety and technical issues. In light of this, a Hardware-in-the-Loop-System (HiLS) testbed to evaluate the performance of connected vehicle applications is proposed. A laboratory powertrain research platform, which consists of a real engine, an engine-loading device (hydrostatic dynamometer) and a virtual powertrain model to represent a vehicle, is connected remotely to a microscopic traffic simulator (VISSIM). Vehicle dynamics and road conditions of a target vehicle in the VISSIM simulation are transmitted to the powertrain research platform through the internet, where the power demand can then be calculated. The engine then operates through an engine optimization procedure to minimize fuel consumption, while the dynamometer tracks the desired engine load based on the target vehicle information. Test results show fast data transfer at every 200 ms and good tracking of the optimized engine operating points and the desired vehicle speed. Actual fuel and emissions measurements, which otherwise could not be calculated precisely by fuel and emission maps in simulations, are achieved by the testbed. In addition, VISSIM simulation can be implemented remotely while connected to the powertrain research platform through the internet, allowing easy access to the laboratory setup.

1. Introduction

Technologies associated with Inter-Vehicle Communications (IVC) and Vehicle-Infrastructure Integration (VII) have not only gained traction in research communities, but also policy makers with the Department of Transportation's proposal for installing communication devices in new vehicles in the near future. Traffic information sharing between vehicles, also known as connected vehicle, is therefore seen as the future of road transportation to improve traffic mobility and safety. Connected vehicle technology also allows better optimization of a vehicle's fuel economy and emissions by utilizing traffic information such as the traffic light Signal-Phase-and-Timing (SPaT) and surrounding vehicles speed information.

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Researches in utilizing connected vehicle technology to optimize fuel use and emissions are mostly done in simulations, while actual testing on real vehicles is limited due to safety, cost and technical challenges. Consequently, the simulation results may not represent the actual fuel and emissions benefits precisely. A Hardware-in-the-Loop-System (HiLS) is therefore proposed to offer the flexibility and accuracy of evaluating the performance of connected vehicle applications. The HiLS is comprised of a microscopic traffic simulator (VISSIM) and a laboratory powertrain research platform. VISSIM is used to simulate a traffic network while the powertrain research platform, which consists of a real engine, an engine-loading device (hydrostatic dynamometer) and a virtual powertrain model is used to represent a single vehicle. A connected vehicle application such as the Cooperative Adaptive Cruise Control (CACC) can be simulated in VISSIM, where a target vehicle is selected to be represented by the powertrain research platform. This is done by sending the simulated target vehicle speed and road condition information from VISSIM to the powertrain research platform in real-time during simulation. This information is used to calculate the vehicle load demand, which is realized by the engine and powertrain. Fuel consumption and emissions from the engine are measured by precise laboratory equipment.

Currently the performance of a vehicle's fuel economy and emissions in traffic is measured through either simulation or by instrumenting the vehicle. First, a simulation-based approach replaces the engine with steady-state fuel-use and emission maps and therefore may not be accurate compared to actual measurements as proposed in the HiLS. Secondly, instrumenting vehicles is time consuming and expensive since it requires major modifications of the vehicles. In addition, equipping large precision measurement devices on small passenger vehicles is challenging for testing purposes.

The HiLS utilizes a real engine for direct fuel and emission measurements. Furthermore, different vehicles can be tested quickly and flexibly by changing the engine and the load settings on the dynamometer. The HiLS can also accommodate large precision measurement devices since it is built in a laboratory setting. Testing connected vehicle applications in a simulated but realistic traffic is more economical without having to instrument multiple vehicles. It is also safer and bypasses the legalities that would otherwise hamper the evaluation of connected vehicle applications in real traffic.

2. Literature review and background

Technologies utilizing IVC and VII (Ma et al., 2009; Paikari et al., 2014) have gained attentions to improve traffic safety and mobility. The Dedicated-Short-Range-Communication (DSRC) used for traffic communication has been proven to be reliable (Bai and Krishnan, 2006; Chen et al., 2007; Kenney, 2011) and field works have been done to evaluate the scalability, security and interoperability of DSRC communications in a real world setting (Dopart, 2014). Rigorous tests were also done to investigate DSRC communication reliability under different cooperative active safety applications (Sepulcre et al., 2013). Reliable IVC and VII make it possible to utilize the abundance of traffic information for numerous connected vehicle applications, including for vehicle fuel consumption and emissions improvements by merging traffic information with powertrain optimization.

Several studies have been conducted to incorporate traffic information into vehicle powertrain optimization (He et al., 2012a, 2012b, 2012c; Manzie et al., 2007). He et al. (2012a) investigated fuel efficiency and emission improvements by implementing VII on a series hybrid-electrical-vehicle (HEV) and Plug-in HEV (PHEV), which is then interpolated to a network-level cost-benefit analysis with a 15-year projection to determine the minimum penetration rate. Some analyses have also been done on the effects of prediction lengths, total mileages, driving cycles and prediction errors, using standard driving cycles, to the fuel consumption of a power-split PHEV (He et al., 2012b). He et al. (2012c) and Manzie et al. (2007) utilized predicted driving cycles and simple kinematic equations to recalculate a less aggressive driving scenario for fuel economy. Future road-grade information has also been used with HEV energy management strategy to save fuel (Zhang et al., 2010). Ranjan and Li (2011) used vehicle load data with a constant-acceleration probabilistic model in road segments, derived from historical traffic data to estimate the total electrical energy use for a specific trip in a pure electrical vehicle. Optimization methods such as Dynamic Programming (Zhang et al., 2010), Stochastic Dynamic Programming (Liu and Peng, 2008), Model Predictive Control or MPC (Borhan et al., 2009) and Equivalent Consumption Minimization Strategy (Zhang et al., 2010; Serrao et al., 2009) were used to incorporate traffic information for fuel and emissions benefits. Mohd Zulkefli et al. (2014) employed the Pontryagin's Minimum Principle (PMP) to implement a real-time HEV powertrain optimization using traffic prediction for fuel benefits. An integrated approach that optimizes vehicle acceleration and HEV powertrain operation simultaneously on a rolling terrain for fuel efficiency using PMP was proposed by Hu et al. (2016). Furthermore, connected vehicle applications, such as the Cooperative Adaptive Cruise Control (CACC), are also explored in terms of fuel savings. Li et al. (2009) used a multi-objective CACC that penalizes high vehicle accelerations for fuel economy utilizing MPC, while Stanger and del Re (2013) utilized a CACC that minimizes fuel based on the Brake Specific Fuel Consumption map with a constant-time headway policy for platooning. Despite numerous efforts to utilize traffic information to optimize fuel and emissions of vehicles in different traffic settings, most results rely on simulation approach which can be inaccurate. This is mainly attributed to the difficulties of conducting real field tests for emerging connected vehicle applications.

Current methods to measure the performance of a vehicle's fuel economy and emissions in traffic are done by either simulation, utilizing fuel consumption and emissions maps or by instrumenting the vehicle, but there are drawbacks of both approaches. A simulation-based approach usually employs steady-state fuel-use and emission maps as a function of the engine torque and speed, which are inaccurate compared to actual measurements especially during engine transients