

Exploring the Impact of Speed Synchronization through Connected Vehicle Technology on Fleet-Level Fuel Economy

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ABSTRACT

It is rare for an attempt towards optimization at the fleet-level when consideration is given to the sheer number of seemingly unpredictable interactions among vehicles and infrastructure in congested urban areas. To close the gap, we introduce a simulation based framework to explore the impact of speed synchronization on fuel economy improvement for fleets in traffic.

The framework consists of traffic and vehicle modules. The traffic module is used to simulate driver behavior in urban traffic; and the vehicle module is employed to estimate fuel economy. Driving schedule is the linkage between these two modules. To explore the impact, a connected vehicle technology sharing vehicle speed information is used for better fuel economy of a fleet including six vehicles. In all scenarios analyzed, the leading vehicle operates under the EPA Urban Dynamometer Driving Schedule (UDDS), while the other five vehicles follow the leader consecutively. Every follower in the fleet was governed by a driver behavior model and their desired speeds may be adjusted according to received speed information of the leading vehicle.

Fuel economy for fleets comprising either all conventional or all hybrid electric vehicles (HEVs) were analyzed. The results show that the shared information contributes to fuel economy improvement more than 4% for the conventional vehicle fleet and at least 7% for the HEV fleet. The simulated vehicle kinematics is also analyzed. Since the analyses show promising results, research of further improving fuel economy with connected vehicle technology under real traffic conditions is recommended.

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INTRODUCTION

Improvement of fuel economy is essential to reducing petroleum consumption, air pollution, and greenhouse gas emissions. To improve fuel economy, major efforts had been made to optimize performance for a single vehicle. However, even a most efficient vehicle made today may barely be able to reach an ideal fuel economy while it gets stuck in traffic, especially under frequent stop-and-go circumstances. That anecdotal observation motivates us to explore the possibility of fuel economy improvement in considering daily traffic.

A major challenge of improving fuel economy with daily traffic is inefficient acceleration due to that a driver has limited knowledge of what the preceding vehicles are going to do. Because of limited capability of human drivers, most of us can only drive according to the dynamic of immediately preceding vehicle. In addition, several other factors, like speed and headway, also have impacts on the reaction. A not-optimized reaction is a source of inefficient acceleration.

Therefore, it is possible to improve fuel economy in daily traffic once the reaction is optimized.

From a single-vehicle point of view, it is intuitively that all vehicles with same characteristics in a fleet should get a same fuel economy if they travel with an exactly the same driving schedule. However, the synchronization can hardly be achieved by human drivers without further assistance. Once there is a lag, the driving schedules will be different and the difference usually represents a worse fuel economy for the followers, even a same type of vehicle is used. Apparently, there is a room for improvement of fuel economy as long as assistance can be provided for the synchronization.

Assuming that the information of preceding vehicles can be shared and the followers can adjust their desired speeds accordingly, we investigated the impact of speed synchronization on fuel economy with simulations. A framework of investigation based on microscopic traffic simulations is proposed. A Wiedemann approach is used to govern car following behavior in simulations. Speed of the

leading vehicle is broadcasted by simulated connected vehicle technology. Fuel economy of all vehicles is evaluated by Autonomie with different ranges of the broadcast.

The purpose of this paper is to explore the potential improvement through connected vehicle technology so that more actual solutions might be established accordingly. Preliminary results show that both conventional and hybrid electric vehicle (HEV) can reach better fuel economy by adjusting desired speed based on the speed message; and HEVs enjoy a greater degree of improvement than their conventional counterparts. Based on the results, it is worthwhile to have more comprehensive analyses of fuel economy improvement in consideration of actual traffic circumstances with the connected vehicle technology.

The rest of this paper is organized as follows: efforts of fuel economy improvement for a single vehicle, car following behavior, and connected vehicle technologies will be reviewed briefly in the next section of Related Work. The proposed framework and its components are introduced in the third section. Simulations we conducted and their limitations are described in the section of Design of Simulation. Results and their meaning are discussed in the section of Results and Discussion. Summary and recommendation can be found at the very end of this paper.

LITERATURE REVIEW OF DRIVING BEHAVIOR INFLUENCES

Drivers always experienced worse fuel economy than expected while they were following other vehicles in urban traffic. From a human factors point of view, research (e.g. [1],[2],[3],[4],[5],[6],[7],[8],[9],[10]) suggests that it is possible to achieve a wide range of fuel economy improvement when appropriate driving behavior is applied. Even simply asking drivers to drive economically may reduce fuel consumption by 10-15 % [2,6]. Indeed, driving is a highly complex task, comprising over 1600 separate tasks over five behavioral levels [11]. Drivers simultaneously control the vehicle, adjust speed and trajectory, deal with hazards, evaluate progress towards their goal, and make strategic decisions such as navigation. Groeger [12] suggested that driver behavior is very much goal-directed, and drivers may have multiple goals (safety, speed, economy etc.), which at any one point in time might be in conflict. Drivers appraise these conflicts and plan their driving accordingly.

Conversely, fuel consumption during engine transient operation are also complicated, vary significantly with each particular driving cycle, and are highly dependent upon the engine calibration. The operation constitutes the largest segment of engine operation over a driving cycle compared to the steady-state one [13]. State-of-the-art engine calibration methods generate a static correlation between the values of the engine variables and the corresponding steady-state operating points. This correlation is incorporated into engine control units to control engine operation. While the engine is

running, these correlations are being interpolated to provide values of the engine variables for each operating point. Theoretical framework and algorithms [14, 15] were developed for making the engine of a vehicle into an autonomous intelligent system capable of learning its optimal operation in real time while the driver is driving the vehicle. Through this approach, the engine progressively perceives the driver's driving style and eventually learns to operate in a manner that optimizes fuel economy.

However, there are still rooms for fuel economy improvement because engine control is affected by various factors. Ericsson [7] focused on independent factors to describe driving patterns and behaviors and to investigate their effects on fuel consumption. He suggested the focus should be on avoiding heavy acceleration, large power demands and high engine speeds. Similarly, Johansson et al. [16] found certain characteristics of driving behavior that were significantly correlated with good fuel economy, such as avoiding unnecessary stops, maintaining low deceleration levels, minimizing the use of 1st and 2nd gears, increasing the use of 5th gear, and block changing gears where possible. Exploiting the vehicle's maximum acceleration capabilities can use up to 60% more fuel than mild or normal acceleration levels [17]. Moreover, LeBlanc et al. [18] proposed that the possibility of substantial potential gains in real-world efficiencies through modification of driver behavior itself (e.g., through training), or for electronic modulation technology between the driver's foot and the throttle to modify a relatively wasteful driver into a more efficient one.

Driving style can have a significant bearing on fuel consumption, but it is often unclear how one should control the car to get the best possible fuel economy. Most of efforts were focused on the improvement for a single vehicle. For example, Hooker et al. [3] employed a forward dynamic programming technique to find optimal control of speed and acceleration for better fuel economy of a test car. Using fuel consumption simulators for 15 cars independently, Hooker [4] aimed at generating reliable advice concerning the optimal driving style to maximize fuel economy. Van Mierlo et al. [9] studied how driving styles and traffic measures can affect fuel consumption and vehicle emissions. The study consisted of evaluating driver behavior and fuel economy over specific driving routes, before and after supplying the drivers with tips on fuel efficient driving practices, to determine whether a change in driver behavior had an impact on fuel economy. Aiming optimal driving styles with respect to driving factors, Malikopoulos and Aguilar [19] proposed an optimization framework with a set of polynomial metamodels reflecting the responses produced by changes of the driving factors.

How to apply the optimal strategies for a single vehicle in daily traffic is a challenge for those approaches to be implemented. Without considering car following maneuver, strategies for single-vehicle fuel economy improvement can barely be implemented. A fleet may represent a simplified version of daily traffic. Newman et al. [20] developed fleet

fuel consumption models for commercial vans and small trucks based on a survey completed by truck drivers in the normal course of their duty. The models used engine displacement, vehicle mass and average speed to predict fuel consumption for petrol and diesel trucks. With the mass term dominating the regression, their models explained 77.4% of the variance for diesel and 86.3% for petrol trucks respectively. Such a model may be useful for finding an optimal strategy for fuel economy by manipulating those variables.

Recent studies took real-world driving conditions into account. Li et al. [21] focused on the servo-loop control design of a Pulse-and-Gliding (PnG) strategy to minimize fuel consumption in automated car following and proposed a switching-based framework for real-time implementation. Up to 20% of fuel economy improvement with the PnG controller was achieved while maintaining precise range bounds so that the negative impact on safety/traffic flow is contained. For maximizing fuel savings from potential drive cycle improvement, Gonder et al. [22] recommended that (1) Leverage applications with enhanced incentives, (2) Use an approach that makes it easy and is widely-deployable to motivated drivers, and (3) Utilize connected vehicle and automation technologies to achieve large and widespread efficiency improvements. They believed that dramatic fuel savings would in reality only be achievable through automated control of vehicles and traffic flow.

Connected vehicle technology offers a possibility to share speed information which may facilitate better fuel economy for followers. The technology focuses on localized Vehicle-to-Vehicle, Vehicle-to-Infrastructure and Vehicle-to-Device Systems (V2X) to improve safety, mobility and environmental applications using Dedicated Short Range Communications (DSRC) using 80211.p and other wireless technologies [23]. With connected vehicle technology, state-of-the-art approaches for improving fuel economy focus on reducing idling time in traffic. By re-routing equipped vehicles, Nobe [24] reported on average a reduction of 17% in CO₂ emission, a 20% decrease in average travel time, and a 25% increase in average vehicle speed for Japan's deployment.

In addition to rerouting, which may not be doable everywhere, we are more interested in whether the connected vehicle technology can facilitate better fuel economy while driving in daily traffic. Ideally, drivers should be able to adjust their desired speed for better fuel economy according to the shared information through vehicle communications. However, the degree of improvement and how the scenario can happen are still unclear. To close the gap, a simulation framework is proposed in this paper for the exploration.

THE PROPOSED FRAMEWORK

Theoretically, all vehicles of the same type should get a same fuel economy if they travel with an exactly same driving schedule. Therefore, a same fuel economy as what the

leader gets can be a target of the improvement because followers always have worse ones. However, the synchronization can hardly be achieved by human drivers alone. The connected vehicle technology discussed in the previous section may provide a way to synchronize consecutive vehicles. To explore the potential with not-populated-yet connected vehicle technology, a framework based on simulations is introduced as follows.



Figure 1. The proposed framework

As shown in Figure 1, the framework has driving schedules as a linkage to bridge microscopic traffic simulation and fuel economy estimation. That makes the framework different from most of conventional approaches because we are not going to manipulate any given driving schedule directly for the improvement. Instead, we are going to facilitate better fuel economy in considering car following maneuver in traffic. Manipulating a given driving schedule without considering surrounding traffic may cause accidents in reality. With this framework, fuel economy may be improved while the followers still can respond to preceding vehicles and traffic controls safely. It implies that recommendations for the improvement based on this framework will be more practical.

A core of the microscopic traffic simulation component in the framework is the driving behavior described by a car following model. There are car following models (e.g. [25], [26], [27]) developed based on different assumptions. Parameters of these car following models can be calibrated with real traffic data. However, it should be noticed that how such a model being implemented, like boundary conditions, may not always be well documented.

For the purpose of this framework, one with appropriate assumptions, e.g. surface street or freeway, can be considered. As long as a car following model is used, the primary driving behavior will be the same. Although the followers' dynamics can be derived directly with a selected car following model, a software package of microscopic