

Impacts of Real-World Driving and Driver Aggressiveness on Fuel Consumption of 48V Mild Hybrid Vehicle

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ABSTRACT

The 48V mild hybrid technology is emerging as a very attractive option for high-volume vehicle electrification. Compared to high-voltage hybrids, the 48V system has a potential of achieving competitive fuel economy with significantly lower incremental costs. While previous studies of 48V mild hybrid systems discussed vehicle configuration, power management strategy and electric machine design, quantitative assessment of fuel economy under real-world conditions remains an open topic. Objectives of this paper are to propose a methodology for categorizing real-world cycles based on driver aggressiveness, and to subsequently analyze the impact of driving patterns on fuel saving potentials with a 48V mild hybrid system. Instead of using the certification test cycles to evaluate the fuel economy, real-world cycles are extracted from 2001-2003 Southern California Household Travel Survey. Subsequently, a consistent energy management strategy is implemented into the vehicle simulation and the real-world fuel consumption reductions are quantified for different levels of driver aggressiveness.

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INTRODUCTION

Societal expectations for minimizing petroleum consumption in transportation and Greenhouse gas emission have been translated into new stringent regulations, such as the 54.5 MPG fleet-wide CAFE (Corporate Average Fuel Economy) requirement in the United States [1]. To achieve the CAFE goal by 2025, different levels of powertrain electrification are considered for passenger cars. Battery Electric Vehicles (BEV) can eliminate direct use of petroleum, but they face associated challenges such as high battery cost and driver range anxiety. On the other hand, Hybrid Electric Vehicles (HEV) still rely on the internal combustion engine for driving range but provide solutions for significant fuel consumption reduction. HEVs are classified into full hybrid, mild hybrid and micro hybrid based on the degree of electrification. While full hybrids can significantly reduce the fuel consumption, their complexity and cost present a barrier to wide-spread adoption. On the other end of the spectrum, the 12V micro-hybrids incorporate only a simple Start&Stop function for modest fuel consumption benefits, but with nearly negligible cost. In between the two extremes are the 48V mild-hybrid systems, which offer an attractive compromise between fuel economy gain and additional system cost. Their typical functions, on top of the Start&Stop, include torque assist and regenerative braking. Furthermore, the electrical shock protection is not required for 48V [2] thus lowering the overall system and maintenance cost.

Concerning 48V mild-hybrid technology, many previous studies have been developed. In [3], several mild hybrid system architectures are showcased, while [4, 5] discuss engine options and electric component sizing. Benchmark for the fuel saving potential with

optimal power management strategy is established in [6, 7], and [8, 9] propose the implementable rule-based and fuzzy-logic strategy, respectively. Simulation based study of the 48V system efficiency potentials in different vehicle is discussed in [10], thus providing useful insights for assessing technology adoption.

While the previous studies provide profound insights into the design, optimization and powertrain efficiency of the 48V mild hybrid system, one drawback is that they were all based on the certification cycles which lack the representativeness of the real-world driving conditions. To overcome this limitation, repetition and scaling of certification cycles can be adopted to mimic real-world driving activities [11, 12]. However, naturalistic driving patterns are much richer in terms of the load/speed distributions [13] and often much more aggressive. Therefore, leveraging a naturalistic driving database is indispensable when analyzing a real-world fuel saving potential and HEV component duty cycles. In this study, 1851 real-world trips from passenger vehicles in the 2001~2002 Southern California Household Survey [14] are imported and coupled with a vehicle model, which is adapted from ADVISOR (Advanced Vehicle Simulator) [15]. The objective is to evaluate a generic mild-hybrid 48V vehicle fuel consumption reduction potential and consider its correlation with driver aggressiveness.

In particular, a novel contribution of this study is the categorization of the driving cycles in a large sample set based on driver aggressiveness, and a subsequent study of its impact on fuel consumption predictions. The definition of driver aggressiveness adopted from a previous study [16, 17] based on analyzing the jerk

trace derived from drive cycle, and defined as the ratio of energy aggregated in the high-frequency range (>0.1 Hz) to energy in the whole frequency range. In this study, a new metric of driver aggressiveness is developed by adding a multiplier to the original definition in [16], which better reflects the reality. Including the new driver aggressiveness in this analysis provides a more comprehensive understanding of the real-world performance of mild hybrid vehicles, facilitates evaluation of the sensitivity of fuel consumption to driving conditions, and offers guidance for the customer-centered design of electrical components.

In order to enable a consistent and fair comparison of results obtained for different levels of driver aggressiveness, a frequency-domain-based power management strategy is designed. The strategy is based on the approach proposed in [17], and it separates power demands into the low-frequency range, met by the engine, and high-frequency range fulfilled by the electric motor. Therefore, engine is assumed to carry the low-frequency, high-amplitude base loads for better fuel efficiency, while battery covers only the high-frequency, low-amplitude fluctuations of the power demands. This assures that the power split between the engine and battery is managed consistently regardless of the driver aggressiveness. This also enables fair comparison of the fuel efficiency potential.

The paper starts with detailed description of the naturalistic drive cycle database, followed by the definition of driver aggressiveness. Vehicle model and power management strategy is explained next. Results section discusses the fuel consumption reduction potential of the 48V hybrid system. It begins with a comparison between 12V and 48V system, followed by the analysis of the 48V system's sensitivity to driver aggressiveness. The paper concludes with a discussion about the battery electrical loads expected with 48V technology in the context of the real-world trips influenced by different levels of driver aggressiveness.

METHODS

This section introduces the naturalistic driving data, reviews the data source and main statistics and defines driver aggressiveness. Next, a compact mild hybrid vehicle and its conventional baseline model is presented. Additionally, the frequency-domain-based power management strategy is developed to facilitate consistency in evaluating the sensitivity of fuel consumption to driver aggressiveness. The behavior of the system is illustrated on the US06 certification drive cycle. Discussion addresses the charge-sustaining features of the strategy, as well as the placement of the engine and electric motor operating points on the respective efficiency maps.

Naturalistic Drive Cycles

The drive cycle data source of this study is a portion of GPS (Global Positioning System) enhanced household travel survey from June 2001 to March 2002 conducted by SCAG (Southern California Association of Governments). De-identified data are publicly available through the U.S. Department of Energy's National Renewable Energy Laboratory (NREL) [14]. The data are recorded with 1Hz sampling rate. After removing outlying high and low

speeds, data spikes and infeasible accelerations, 1851 trips from 292 passenger vehicles with a total driven distance of about 25,000 km are adopted in this study.

The statistical distributions of travel distances, cycle mean velocity, idle percentage and mean positive acceleration rates are shown in Figure 1. A large variety of driving conditions are contained in this database; hence, it well reflects the real-world driving conditions. The drive cycles with distance less than 1 mile (1.6 km) are intentionally excluded.

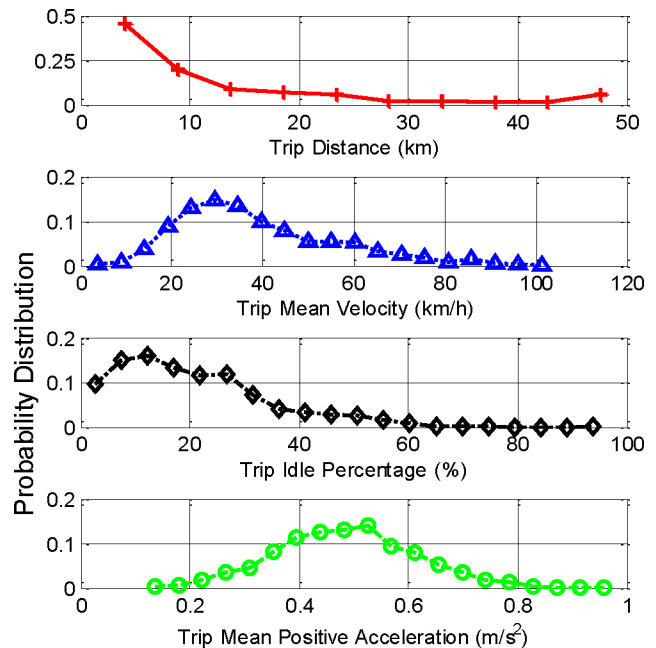


Figure 1. Distribution of trip distance, trip mean velocity, trip idle percentage, trip mean positive acceleration in the SCAG naturalistic drive cycle database

Driver Aggressiveness

For the purpose of this study, the 1851 real-world trips are further categorized according to driver aggressiveness. It abstracts the frequency of changing the vehicle power demand, which is essentially equivalent to the frequency of changing power/brake pedal position. However, the impact of traffic conditions are filtered from the signals in order to extract driving aggressiveness as an indication of personal driving style. In other words, instead of determining driver aggressiveness based on absolute values of power demands, the new metric isolates only the effect of driver behavior.

The driver aggressiveness definition proposed in [16] was based on above concept. It defined the driver aggressiveness in frequency-domain as follows: a drive cycle's jerk trace, i.e. the second derivative of speed trace, is transformed from time-domain to frequency domain via Fast Fourier Transform (FFT) illustrated by periodogram in Figure 2. The low-frequency (LF) range (<0.1 Hz) is attributed to traffic conditions, while the high-frequency (HF) range (>0.1 Hz) driving activity corresponds to driving aggressiveness. A driver aggressiveness metric, denoted as ripple aggressiveness in [16], was originally constructed as the ratio of energy aggregated in the high-frequency domain to the ratio of energy aggregated in complete frequency domain of the jerk trace Fourier transform, as in Eq. (1).

Original Driver Aggressiveness =

$$\frac{HF}{LF + HF}$$

(1)

However, Figure 3 illustrates an inconsistency that needs to be addressed. Both trips in Fig. 3 display nearly the same driver aggressiveness, as defined by Eq. (1), even though the acceleration rates of the trip (excluding idling periods) in Fig. 3a are much higher compared to the trip in Fig. 3b. A closer examination indicates that different magnitudes of periodograms might be the cause for the inconsistency, and ought to be included in the metric. Hence, a multiplier is added to the original definition of driver aggressiveness and the new definition is shown in Eq. (2). The modified driver aggressiveness is better correlated with the cycle acceleration rates.

Regarding Eq. 1 and 2 the LF is the energy aggregated in the low frequency range by summing the low frequency components below 0.1 Hz; HF is the energy aggregated in the high frequency range by summing the high frequency components above 0.1Hz. Mean (periodogram) is the mean value of the periodogram across the whole frequency range.

The cumulative distribution of modified driver aggressiveness in the SCAG database is given in Figure 4. The 1851 cycles are categorized into calm, normal and aggressive trips by evenly dividing the cumulative distribution in Figure 4.

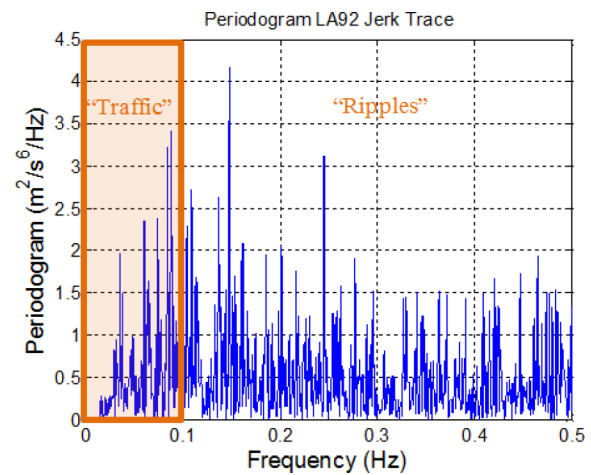


Figure 2. Periodogram of LA92 drive cycle's jerk trace

$$\text{mean (periodogram)} * \frac{HF}{LF + HF}$$

(2)

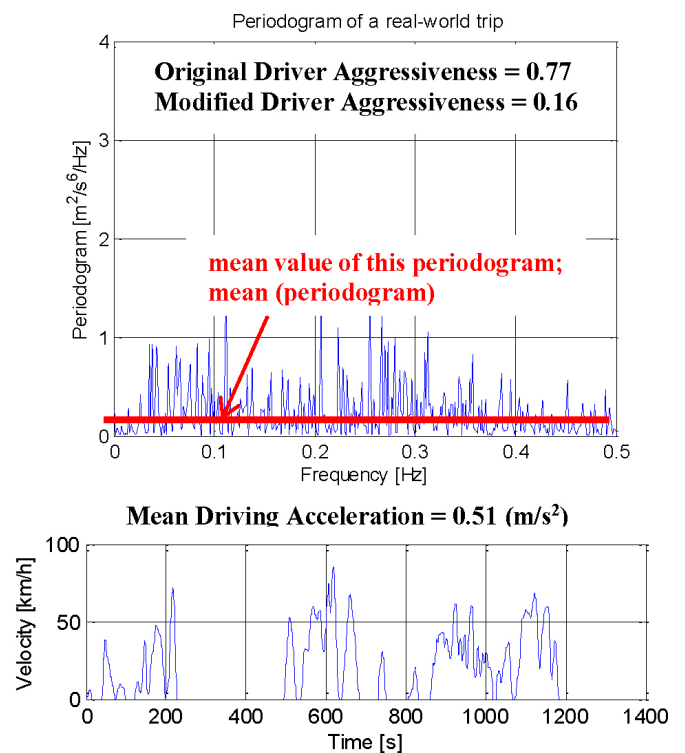
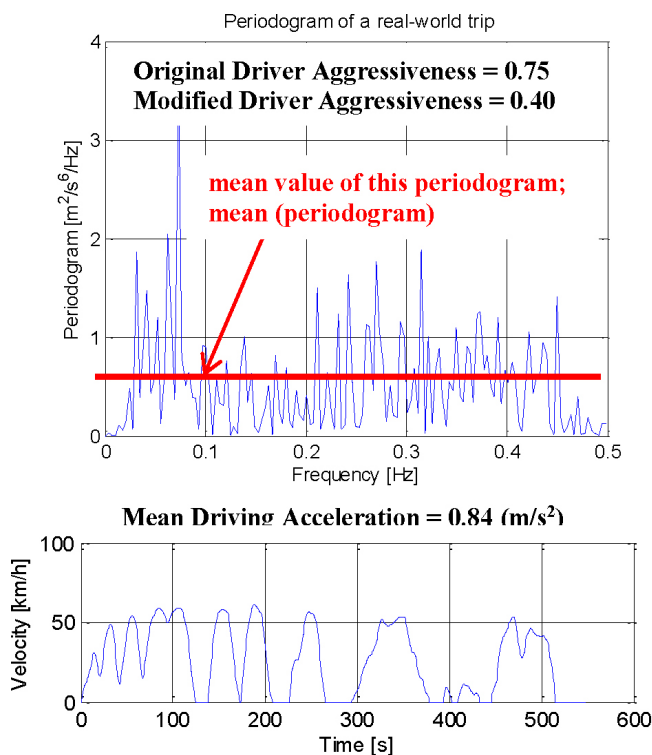


Figure 3. Example periodograms of two real-world trips and their corresponding speed traces: two driving activities on secondary road at moderate speeds. Figure 3(a) on the left, 3(b) on the right