

Quantification of Drive Cycle's Rapid Speed Fluctuations using Fourier Analysis

Zifan Liu, Andrej Ivanco, and Zoran Filipi
Clemson-ICAR

ABSTRACT

This paper presents a new way to evaluate vehicle speed profile aggressiveness, quantify it from the perspective of the rapid speed fluctuations, and assess its impact on vehicle fuel economy. The speed fluctuation can be divided into two portions: the large-scale low frequency speed trace which follows the ongoing traffic and road characteristics, and the small-scale rapid speed fluctuations normally related to the driver's experience, style and ability to anticipate future events. The latter represent to some extent the driver aggressiveness and it is well known to affect the vehicle energy consumption and component duty cycles. Therefore, the rapid speed fluctuations are the focus of this paper. Driving data collected with the GPS devices are widely adopted for study of real-world fuel economy, or the impact on electrified vehicle range and component duty cycles. However, the accompanying signal noise poses a challenge, and needs to be separated from realistic rapid speed fluctuations. Filtering is commonly used, but aggressive smoothing technique can lead to loss of useful driving information. In contrast, mild smoothing technique can lead to under-filtering and inclusion of redundant information. The main contribution of this paper is a proposed metric, denoted as "Ripple Aggressiveness", to quantify the rapid speed fluctuations over a drive cycle based on the Fourier analysis. This metric allows assessment of the filtering level, and detection of over-filtering, or under-filtering. The data used to develop and demonstrated the new technique are from the 2001~2002 Southern California Household Travel Survey, 2010~2012 California Household Travel Survey, 2001~2005 Michigan Road Departure Crash Warning System Field Operational Tests, and EPA dynamometer drive schedules. The newly developed metric is correlated with fuel economy using the vehicle simulation, and the results show a positive correlation between Ripple Aggressiveness and vehicle fuel consumption. Hence the metric can also be used as a surrogate to quantify the driver aggressiveness.

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INTRODUCTION

Cycle aggressiveness is an abstract term related to a vehicle's energy consumption rate over a specific drive cycle and sometimes addressed alternatively as driving style, driving aggressiveness, etc. Previous studies had tried to quantify the cycle aggressiveness with metrics based on velocity, acceleration and jerk [1, 2, 3, 4]. Relationships between these metrics and energy consumption rates had been established to assist in various applications such as component design, eco-drive coaching and hybrid vehicle energy management [4, 5, 6]. However, one drawback of these metrics is that they are mostly average-based, percentile-based or variance-based. In other words, they capture only the general trend of drive cycles, missing some interesting details such as the rapid fluctuations of the speed traces. These fluctuations cause a significant fuel economy penalty in gasoline/diesel engine powered vehicles, while their impact on a hybrid vehicle depends on the propulsion system design and control. A metric is proposed in this study to facilitate quantitative analysis and direct comparison of the rapid speed fluctuations. Considering its contribution to overall cycle aggressiveness and its own characteristics, we denote the metric as Ripple Aggressiveness in the following sections.

Recognizing the limitations of certification drive cycles and the significance of naturalistic drive cycles, the driving data collection from real-world driving had been realized in several large interdisciplinary projects [7-8]. In actual applications, the Global Positioning Systems (GPS) data acquisition devices are becoming popular due to cost-effectiveness and user-friendliness. Nevertheless, due to the inherent operating behaviors of these devices, several sources of errors in the collected driving data had been discussed in [9], and summarized as: duplicate records, outlying records, signal drift, signal loss, and signal noise. A necessary step before downstream applications of the GPS collected data is to correct those errors. Of particular interest in this study, the signal noise is emphasized due to its potential impacts on the Ripple Aggressiveness. This is visualized in Figure 1 with the GPS raw data and smoothed data. Common way of eliminating noise is to implement some filter. However, there is no clear standard concerning the intensity of the filter applied on the recorded speed trace. Over-filtering often occurs to assist in the vehicle dynamometer tests. However, higher frequency fluctuations can be real, and will significantly impact energy consumption predictions. Hence, distinguishing between noise and real speed ripples is critical, and a new method is needed to guide proper filtering.

This study aims to distinguish real world driving signal from signal noise with a quantitative metric based on Ripple Aggressiveness. To illustrate this, the paper is organized as follows. Firstly, all real-world driving data used in this study are introduced. Then the adopted methodologies are briefly reviewed, followed by an application to the driving data. Finally, detailed results are summarized, including the distribution of Ripple Aggressiveness among the real-world driving data, detection of over- or under-filtering, and the impact of Ripple Aggressiveness on the energy consumption.

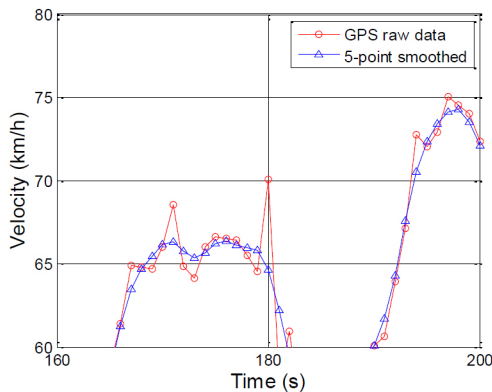


Figure 1. An example of GPS raw data and smoothed data.

DATA SOURCE

This study uses detailed transportation data from a variety of travel surveys which are publicly accessible in the Transportation Secure Data Center (TSDC) by the National Renewable Energy Laboratory (NREL) [8]. Specifically, the 2010-2012 California Household Travel Survey (abbreviated as “2010 California Survey”) and 2001-2002 Southern California Regional Travel Survey (abbreviated as “2001 California Survey”) are investigated to define the Ripple Aggressiveness.

Using GPS devices to record speed traces of individual trips, which are from “Engine-On to “Engine-Off”, TSDC provides not only the processed driving data but also the raw driving data. The data processing techniques deal with common sources of errors in GPS data including duplicate records, outlying records, signal drift, signal loss, and signal noise [9]. While TSDC applies in-house filters to address above errors, the availability of both raw data and processed data offers a chance to examine the potential filtering effects on cycle aggressiveness, with which this study concerns.

Besides the above, 181 trips from the 2001-2005 Michigan Road Departure Crash Warning System Field Operational Test project [10] (abbreviated as “2001 Michigan Project”), which were collected directly from the onboard Controller Area Network (CAN) bus, are included for a special reason. Since they are free of GPS-related high-power noise, the CAN data are used to calibrate the real distribution of Ripple Aggressiveness from naturalistic drive cycles.

METHODS

Every speed trace is a finite-length signal characterizing a driving event (from start to stop). Vehicle speed traces can be regarded as the discretized version of continuous-time driving velocity. In other words, the driving data from the surveys are sampled from real-world driving patterns. The sampling frequency for GPS devices is 1 Hz in this study.

Any discrete-time signal can be studied in both the time domain and frequency domain. The bridge between the two domains is the Fourier theory, a branch of harmonic analysis [11]. Several Fourier operators (direct and inverse) can be applied to discrete-time signals.

- Discrete Fourier Transform (DFT) maps length- N signals into a set of N discrete frequency components;
- Discrete Fourier Series (DFS) maps N -periodic infinite signals into a set of N discrete frequency components;
- Discrete-Time Fourier Transform (DTFT) maps infinite signals into the space of 2π -periodic function of a real-valued argument.

This study deals with finite-length signal; therefore, the DFT operator is chosen as basis for development of new metrics.

Discrete Fourier Transform

Given a length- N signal, $x(n)$ in discrete time domain, with the Discrete Fourier Transform (DFT), the Fourier analysis formula of the signal is in Equation (1):

$$X(k) = \sum_{n=0}^{N-1} x(n)W_N^{nk}, k = 0, \dots, N-1 \quad (1)$$

In Equation (1), $W_N = e^{-j\frac{2\pi}{N}}$.

Therefore, a finite length- N signal in time domain can be transferred to frequency domain and decomposed into a set of N sinusoidal oscillatory components, characterized by the $X(k)$ in frequency domain. $X(k)$, which contain the magnitude and initial phase of each oscillator, corresponds to the digital frequency of $\frac{2\pi k}{N}$ ($k = 0, 1, \dots, N-1$). If denote the abstract dimensionless digital frequency as $\omega_{digital}$, it relates to real frequency f_{real} in Hertz as in Equation (2):

$$f_{real} = \frac{f_s}{2\pi} \omega_{digital} \quad (2)$$

f_s is the sampling frequency of the signal. Due to the phenomenon of *Aliasing* [11], the maximum real frequency for the signal is $f_s/2$ for real-valued signal and f_s for complex-valued signal. Since for all available speed traces in this study, the speed values are all real and the sampling frequency is 1Hz, the real-frequency range should be (0: 1/N: 1/2).

The transfer from frequency domain to time domain is also feasible with Inverse Discrete Fourier Transfer (IDFT), or say, the Fourier synthesis, as illustrated in Equation (3) for above signal:

$$x(n) = \frac{1}{N} \sum_{k=0}^{N-1} X(k) W_N^{-nk}, n = 0, \dots, N-1 \quad (3)$$

DFT is a numerical tool which deals with finite signals and defines a finite number of operations, and the Fast Fourier Transform (FFT) is commonly used as the computation-efficient algorithm to accelerate the DFT. There are several techniques to implement the FFT, such as the Cooley-Tukey algorithm [12] and Rader's algorithm [13].

Periodogram

Based on DFT, one more useful relationship between the $X(k)$ and $x(k)$ of a signal is in the viewpoint of energy conservation, based on the Parseval's theorem [11] as described in Equation (4).

$$\sum_{n=0}^{N-1} |x(n)|^2 = \frac{1}{N} \sum_{k=0}^{N-1} |X(k)|^2 \quad (4)$$

As the left side of Equation (4) represents the energy of the finite signal in time domain, it equals to the energy in the frequency domain normalized by $1/N$, as shown on the right side of Equation (4). All the terms on the right side of Equations, described as $\frac{1}{N} |X(k)|^2$, make up the so-called *Periodogram*. Specifically for the zero-mean signals, Equation (4) would have a straightforward physical interpretation: the area under the Periodogram approximates to the variance of the signal in time domain with long signal length and high recording resolution.

With all above techniques, every available speed trace can be observed in both the time domain and the frequency domain, yielding a new insight on the driving data.

APPLICATION

To apply Fourier analysis on the driving data, some pre-processing is preferred to investigate the relevant details of this study. This section showcases these steps before the final results are described with an example based on the LA92 (Air Resources Board Dynamometer Driving Schedule) drive cycle [14].

Speed Trace

Figure 2 shows the speed trace of LA92 drive cycle. Even though the speed trace seems continuous, it is actually discrete-time signals with the sampling time of 1 second.

To better view a speed trace in frequency domain via DFT, several pre-processing steps have to be completed in time domain. The sequential steps include:

- Deleting the Idle-period;

Since the idle-periods do not affect the Ripple Aggressiveness discussed in this study, and would significantly affect the frequency components if included, they should be deleted.

- Mean-Adjusting;

Our investigating Ripple Aggressiveness will not be affected by subtracting the mean value from every speed point. By mean-adjusting, the Direct Current (DC) component [11] at the 0 Hz in the frequency domain which can be too big and disguise other frequency components will be deleted.

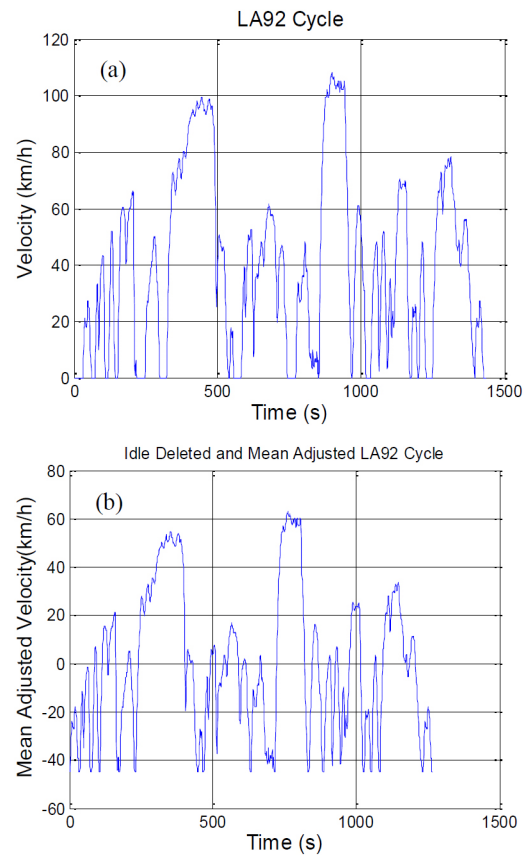


Figure 2. (a) Original LA92 drive cycle, (b) Idle-deleted and Mean-adjusted LA92 drive cycle.