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# Effects of driving style on the fuel consumption of city buses under different road conditions and vehicle masses

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ABSTRACT

The variance in fuel consumption caused by driving style (DS) difference exceeds 10% and reaches a maximum of 20% under different road conditions, even for experienced bus drivers. To study the influence of DS on fuel consumption, a method for summarizing DS characteristic parameters on the basis of vehicle-engine combined model is proposed. With this method, the author proposes 26 DS characteristic parameters related to fuel consumption in the accelerating, normal running, and decelerating processes of vehicles. The influence of DS characteristic parameters on fuel consumption under different road conditions and vehicle masses is quantitatively analyzed on the basis of real driving data over 100,000 km. Analysis results show that the influence of DS characteristic parameters on fuel consumption changes with road condition and vehicle mass, with road condition serving a more important function. However, the DS characteristics in the accelerating process of vehicles are decisive for fuel consumption under different conditions. This study also calculates the minimum sample size necessary for analyzing the effect of DS characteristics on fuel consumption. The statistical analysis based on the real driving data over 2500 km can determine the influence of DS on fuel consumption under a given power-train configuration and road condition. The analysis results can be employed to evaluate the fuel consumption of drivers, as well as to guide the design of Driver Advisory System for Eco-driving directly.



## Introduction

Fuel consumption in the global traffic transportation field will continue to increase, and daily consumption is predicted to reach 60 million barrels in 2035, thereby accounting for 61% of the total fuel oil output (He et al., 2012). Under the dual pressure recently imposed by of energy and environmental crises, multiple technologies, including the power-train optimization technology used for hybrid electric cars and engine optimization technologies such as Start–Stop systems, have been developed in the traffic transportation field to reduce vehicle fuel consumption and emissions. And there is a new technology to save fuel by guiding drivers in changing their driving style (Andrieu and Pierre, 2012; Barth and Boriboonsomsin, 2009; Larsson and Ericsson, 2009; Syed et al., 2008; Wu et al., 2011).

Numerous studies have shown that DS has important implications on vehicle fuel consumption. Gonder et al. (2012) conducted experiments on a light-duty vehicle and found that different DSs can generate a difference of approximately 30% in fuel consumption in the urban driving cycle. The difference can reach 20% in the high-speed way driving cycle. They also

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believe that by changing DS, aggressive drivers can reduce fuel consumption by 20%, whereas mild drivers can decrease consumption by 5–10%. Sivak and Schoettle (2011) discovered through an investigation that among the fuel-saving technologies of light-duty vehicles through which drivers can make strategic decisions, the method of changing DS generates the best fuel-saving result (about 25%). However, the fuel-saving result from engine tuning is less than 10%. As for heavy-duty vehicle, Liimatainen (2011) found that different DSs can generate a difference of approximately 20% in fuel consumption for city buses. To weaken the influence of defective DS on fuel consumption, studying the influence mechanism of DS is necessary. Bingham et al. (2012) discovered that the DS can also make about 30% energy consumption difference for electric vehicle. Through literature researches we can find that this research is composed of two parts:

(1) determination of the characteristic parameters that should be used to describe DS; and
(2) analysis of the effect of such characteristics on fuel consumption.

Two main methods for extracting DS characteristics are used in the first part. The first method is the extraction of the speed profile characteristics to replace DS characteristics, which include vehicle speed, acceleration, standard deviation of speed, and jerk. Ericsson (2001) and Berry (2010) both adopted this method. The second method is the extraction of DS characteristics on the basis of driver operations. This method requires the collection of the driving operations of drivers. These operations include those of the gear, accelerator pedal, brake pedal, clutch, and steering wheel. Characteristic parameters, such as gear shift timing, average depth of accelerator pedal, and the standard deviations of accelerator pedal depth and of steering wheel angle, are summarized on the basis of the said operations to describe DS. Lee and Son (2011) used this method to obtain 18 characteristic parameters for describing DS in the high-speed way driving cycle. The first method is easy to implement because speed can be measured easily, and only one object requires analysis. However, speed profile is the final result of a series of driver operations, and some DS characteristics extracted from such profile may be lost. The extraction, which is based directly on the driver operations, can retain all DS characteristics. However, this method is very complicated. More parameters (gear, accelerator pedal, brake pedal, clutch, and steering wheel) have to be collected. Moreover, driver operations change rapidly, which imposes a high sampling frequency requirement. In addition, when more objects need analysis, summarizing the DS characteristics related to fuel consumption becomes difficult.

For the second part, two methods are used to evaluate the influence of DS on fuel consumption. The first approach is the model-based analysis method, whereas the second is the statistical analysis method based on real driving data. The model-based analysis method uses the engine fuel consumption, vehicle, and driver models to analyze the influence of DS characteristics on fuel consumption directly. This method is efficient and low cost, but has high model accuracy requirements. According to the research conducted by Delice and Ertugrul (2007), an accurate driver model has to identify approximately 10,000–50,000 parameters. Meanwhile, obtaining the transient engine fuel consumption model is hard, and has always been a research hotspot (Chiara et al., 2011; Giakoumis and Alafouzos, 2010; Shi et al., 2013). Thus, the model-based analysis method is mainly used to study driver behavior under some simple road conditions (McGordon et al., 2011), such as the high-speed way driving cycle. The statistical analysis method based on real driving data requires the collection of a large amount of data as research basis. The actual data collected contain a large number of random factors, such as weather, vehicle mass, and traffic jam. Only when the data size is sufficient can these factors be prevented from interfering with the analysis results (Ericsson, 2001). The statistical analysis method may omit some characteristic parameters because of the lack of theoretical support.

China has over 400,000 buses with fuel consumption that exceeds 10 million tons annually. Hence, the fuel saving potential is huge. Buses have fixed routes, and drivers have a strict duty schedule. Thus, this study selects city buses as research objects. First, the vehicle-engine combined model is established to analyze which DS characteristics may affect fuel consumption. No quantitative analysis is involved to avoid the problem of inaccurate driver and transient engine fuel consumption models. The data collection system adopted in this research is then introduced. With this system, the real driving data over 100,000 km are collected to exclude random factors from influencing the analysis results. On the basis of these data, the influence of DS characteristic parameters on fuel consumption under different road conditions and vehicle masses is quantitatively analyzed. Meanwhile, the minimum sample size necessary to analyze such influence is also calculated. The analysis results can be employed to evaluate the fuel consumption of drivers, as well as to guide the design of Driver Advisory System for Eco-driving directly.

## Methodology

### *Method of extracting driving characteristics*

#### *Vehicle-engine combined model*

For traditional vehicles, drivers operate the clutch, brake pedal, accelerator pedal, gear, and steering wheel on the basis of their own habits according to the corresponding traffic conditions. Apart from the operation of the steering wheel, other operations control the running of the engine directly or indirectly through the power-train system. The working condition of the engine determines the fuel consumption of vehicles. Therefore, the relationship between the said driver operations and the working condition of the engine has to be assesses first before analyzing if the influence of driving style on fuel