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Fast computing and approximate fuel consumption modeling for Internal Combustion Engine passenger cars

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ABSTRACT

This article presents a fuel consumption model, SEFUM (Semi Empirical Fuel Use Modeling), and its comparison with three models from the literature on a 600 km experimental database. This model is easy to calibrate with only a few required parameters that are provided by car manufacturers. The test database has been built from 21 drivers who drove in two conditions (normal and ecodriving) on a 15 km trip. For the model evaluation, three indicators have been selected: instantaneous fuel use root mean square error, cumulated error and computation time in order to evaluate the accuracy both in cumulated and instantaneous fuel use and to estimate computation time of each model. Results tend to prove that the model is able to compute rapidly (maximum of 1500 simulated kilometers under Matlab) in comparison to all other models while ensuring a high accuracy and precision for cumulated and instantaneous fuel use.

1. Introduction

The main objective of this paper is to present the development, validation and limits of SEFUM, Semi Empirical Fuel Use Modeling, which has been designed to be an accurate and fast computing fuel consumption model for Internal Combustion Engine with a simple calibration procedure. This kind of fuel consumption model can be required for estimating fuel use in micro traffic simulation knowing that it describes the traffic network at the vehicle level and can model thousands of vehicles simultaneously. In this context, precisely estimating the fuel consumption of each individual in an accelerated time scale is challenging (micro traffic simulator can model 10 h of traffic in one hour).

These models are also useful for computing optimal speed profiles aiming at minimizing fuel use: many algorithms have been developed to reduce fuel use of passenger cars by acquiring the road characteristics in front of the vehicle. These algorithms, often relying on operational research methods, are time consuming, and each of its calculation step calls the fuel consumption model of the considered vehicle. Furthermore, the complexity of the computation increases with the predicted distance.

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Then, fast computing models are needed for database enrichment. Databases containing speed profile can be enriched with modeled fuel consumption data. These databases can be constituted of million of kilometers, at medium frequency (20 Hz). Computing fuel use from these data can be time consuming and may generate server latencies.

Furthermore, these models can be used for in-line fuel use estimation on nomadic devices. Smartphone, tablets, GPS and other nomadic devices are more and more used in vehicles for navigation or driving assistance purposes. These systems may not be connected to the vehicle and thus, may lack of vehicle data such as engine speed. Furthermore, in order to reach high frequencies, the model has to be as quick as possible to avoid any latencies in the process. At 20 Hz, which is a medium frequency, the model has 50 ms to compute fuel use.

Finally, simulating fuel use sensors in driving simulator platforms also requires efficient fuel use modeling. Real time driving simulator creates a virtual environment to immerge the driver in a realistic world where he drives a simulated vehicle. This kind of software requires fast computing fuel use modeling in order to warrant the simulation real time characteristics.

In this paper, a semi-empirical fuel use modeling, designed in order to minimize the computation time, is compared to models from the literature. In SEFUM model, several assumptions have been taken that might have an impact on its accuracy in order to reduce its computation delays. The aim of this paper is then to present and evaluate the SEFUM model.

The remainder of this paper is organized as follows: Section 2 presents a brief overview of fuel consumption models as detailed in the literature. Section 3 develops the methodology of this work. Section 4 details the SEFUM model and Section 5 its validation. Section 6 discusses the limits of the proposed work and Section 7 concludes the paper.

2. State of the art models

A wide range of fuel consumption models is available in the literature. They vary mainly depending on the vehicle from motorcycle to heavy duty vehicles but also according to the engine type (thermal, electric, hybrid...). In this study the case of the Internal Combustion Engine (ICE) of lightweight vehicles will be analyzed. There exist different ways of classifying fuel consumption models. The first way defines two main categories.

- The first being Forward facing, where the complete powertrain from the gas pedal to the wheel is modeled and a simulated driver regulates acceleration and deceleration to fit a provided speed profile. A well-known "forward-facing" model is ADVISOR developed under Matlab by the US Department of Energy (Markel et al., 2002).
- The second category, called Backward facing uses the speed profile as input to compute the different forces from the wheel to the engine (gravitational, inertial, rolling resistance, aerodynamic drag, friction forces) and then estimates the fuel use with a transfer function depending on the vehicle type. Most of existing fuel use models are within this category as they are simpler and cheaper to implement. Several backward modelings, depending on the vehicle category, are presented in Nam and Gianelli (2005).

According to the modeling objectives, the efforts of this study are concentrated on a Backward facing modeling as it is supposed to be faster to compute and to be simpler to calibrate than Forward facing models. Furthermore, according to this study objectives, the provided speed profiles are always considered to be feasible as they have been produced by humans on the considered test vehicle.

Another model classification relies on the modeling principles: engine map based, regression based or load based (Cappiello et al., 2002). Furthermore, some models can be considered hybrid, being mainly load based and regression based but other combinations exists.

- In the first category fuel use is computed from an engine map described as a matrix (lookup table). This has the advantage to be accurate but it requires a large number of data for each car and sparse matrices might be a challenge.
- In the second category, a regression has been performed on real experiments to build a statistical model. This limits the physical interpretation of results and might overfit the calibration by adding to many explanatory variable. Also, the calibration has to be done for all vehicles. This last drawback has been overcome in the work of Cappiello et al. (2002).
- In the third category, physical equations simulate the efforts generating the fuel consumption. These models are complex and require a high computational effort. CMEM, from the University of Riverside, is a modal modeling based on physics (Barth et al., 1996) as well as Ben-Chaim et al. (2013) but other modelings like Virginia Tech VT-CPFM (Rakha et al., 2011) have been developed and showed very accurate results. The NCHRP report 720 also presents several ways of developing load-based models (Chatti and Zaabar, 2012).
- Hybrid modelings aim at combining models advantages to reduce computation time, reduce calibration efforts and increase the models accuracy. Among them, load-regression based are the most common but others can be found such as engine map-regression as in Lee et al. (2011) where the engine map is fitted from experimental measurements.

3. Methodology

The first step of this work consisted in developing the modeling mathematics. This has been done by combining a physical approach and an empirical approach. Then, the model can be classified in a load-regression, hybrid category and