Comprehensive Fuel Consumption Model based on Instantaneous Vehicle Power

Hesham Rakha[1], Kyoungho Ahn[1], Kevin Moran[2], Bart Saerens[3], and Eric Van den Bulck[3]
Virginia Tech Transportation Institute, Virginia, USA[1], NAVTEQ Corporation, USA[2], Department of Mechanical Engineering, K.U. Leuven, Belgium[3]

Paper Objectives

- This study develops two simple fuel consumption models can be *easily implemented within microscopic traffic simulation software, vehicle operational control systems, a real-time eco-driving system*.

Introduction

- Vehicle fuel consumption depends on many factors that may not be captured easily by a single mathematical model. Some of the factors include: engine design, vehicle age, driver behavior, road topography, fuel properties, resistive forces on the vehicle, ignition technology, cylinder head design, friction inside the engine, temperature, humidity level, and many other factors.
- Compromising between simplicity and accuracy has always been a difficult task for any modeler so the challenge is to identify the key parameters for consideration in a model without creating a complicated model that poses a calibration challenge.
- A simple, accurate, and efficient model is one of the key elements of new fuel consumption modeling.
- This study presents a new power-based microscopic fuel consumption model entitled the Comprehensive Power-based Fuel Consumption Model (CPFM).
- There are four major criteria to be considered for the proposed fuel consumption model: real-time computation, accuracy, model structure, and model calibration simplicity. The proposed model should be
  - provide real-time computations instead of aggregated trip fuel consumption estimates.
  - provide reasonable accuracy with the fewest input variables.
  - simple to reduce the computational load.
  - applicable for general vehicle populations, and should be calibrated using publicly available data.

Power-based Microscopic Fuel Consumption Models

- Vehicle fuel consumption levels are typically derived from a relationship between instantaneous fuel consumption rates and instantaneous measurements of various explanatory variables including vehicle power, force (or tractive effort), acceleration, speed, and/or roadway grade.
- Vehicle power can be computed as the product of the total force exerted by the vehicle and the vehicle velocity. A sample fuel consumption model is formulated as follows, where α1 is the fuel consumption rate (g/s or l/s) for idling conditions and P(t) is the instantaneous total power in kilowatts (kW). The model coefficient (β1) are estimated by calibration process.

$$F(t) = \begin{cases} a_1 + b_1 P(t) & P(t) \geq 0 \\ a_1 & P(t) < 0 \end{cases}$$

- Most models require the calibration of the model parameters by collecting field data. This exercise is time consuming and does require that some form of vehicle instrumentation.

Proposed Modeling Frameworks

- Two power-based second-order polynomial models are proposed in this paper. These models are entitled Comprehensive Power-based Fuel Consumption Model-1 and -2 (CPFM-1 and CPFM-2). The two CPFM models are formulated as

$$FC(t) = \begin{cases} a_0 + a_1 P(t) + a_2 P(t)^2 & P(t) \geq 0 \\ a_0 & P(t) < 0 \end{cases}$$

$$FC(t) = b_0 w(t) + b_1 P(t) + b_2 P(t)^2$$

- The power at any instant t is computed as

$$P(t) = \left(\frac{R(t) + 1.04 m a(t)}{3600 h_d}\right) v(t)$$

- The first model does not require any engine data given that the power exerted by a vehicle is a function of the vehicle speed and acceleration level, which can be measured directly using non-engine instrumentation like for example a Global Positioning System (GPS).
- The second model requires engine data in addition to external data and thus can be used to model eco-drive gear-shifting strategies but does require the explicit modeling of the vehicle engine.

CPFM-1 Model

- The idling fuel consumption rate for the Comprehensive Power-based Fuel Model (CPFM-1) is estimated as

$$a_0 = \max\left(\frac{P_{mfo} w_{idle} d}{22164 \times QN}, \frac{F_{city} - F_{hwy}\dfrac{P_{city}^2}{P_{hwy}^2}}{T_{city} - T_{hwy}\dfrac{P_{city}^2}{P_{hwy}^2}}, e \times \frac{F_{city} - F_{hwy}\dfrac{P_{city}}{P_{city}}}{T_{city} - T_{hwy}\dfrac{P_{city}}{P_{city}}}\right)$$

$$a_1 = \frac{\left(F_{city} - F_{hwy}\dfrac{P_{city}^2}{P_{hwy}^2}\right) - \left(T_{city} - T_{hwy}\dfrac{P_{city}^2}{P_{hwy}^2}\right) a_0}{P_{city} - P_{hwy}\dfrac{P_{city}^2}{P_{hwy}^2}}$$

$$a_2 = \frac{\left(F_{city} - F_{hwy}\dfrac{P_{city}}{P_{hwy}}\right) - \left(T_{city} - T_{hwy}\dfrac{P_{city}}{P_{hwy}}\right) a_0}{P_{city}^2 - P_{hwy}^2\dfrac{P_{city}}{P_{hwy}}} \qquad e = 10\text{E-}06$$

Where P_{mfo} is the idling fuel mean pressure (400,000 Pa); ω_{idle} is the idling engine speed (rpm); d is the engine displacement (liters); Q is the fuel lower heating value (43,000,000 J/kg for gasoline fuel); N is the number of engine cylinders; F_{city} and F_{hwy} are the total fuel consumed for the EPA city and highway driving cycles (liters); T_{city} and T_{hwy} are the durations of the city and highway cycles (1875s and 766s, respectively); P_{city} and P_{city}^2 are computed as the sum of power and power squared exerted each second over the entire cycle.

- The first term of the idling fuel consumption rate is an average operating point method that was proposed by Guzzella and Sciarretta.
- α_1 and α_2 can be computed by solving a system of two linear equation as

$$F_{city} = T_{city} a_0 + P_{city} a_1 + P_{city}^2 a_2$$

$$F_{hwy} = T_{hwy} a_0 + P_{hwy} a_1 + P_{hwy}^2 a_2$$

CPFM-2Model

- The CPFM-2 model can be calibrated in a similar fashion.

$$b_0 = \frac{P_{mfo} d}{22164 \times QN}$$

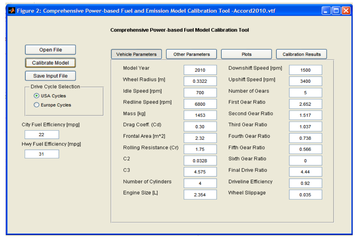
$$b_1 = \frac{\left(F_{city} - w_{city} b_0 - P_{city}^2 b_2\right) + \left(F_{hwy} - w_{hwy} b_0 - P_{hwy}^2 b_2\right)}{2}$$

$$b_2 = \frac{\left(F_{city} - F_{hwy}\dfrac{P_{city}}{P_{hwy}}\right) - \left(w_{city} - w_{hwy}\dfrac{P_{city}}{P_{hwy}}\right) b_0}{P_{city}^2 - P_{hwy}^2\dfrac{P_{city}}{P_{hwy}}} \qquad 1\text{E-}06$$

Where ω_{city} and ω_{hwy} parameters that are computed as

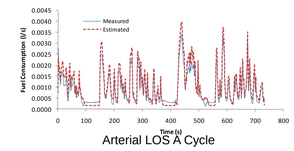
$$w_{city} = \sum_{t=0}^{T_{city}} w(t), \quad w_{hwy} = \sum_{t=0}^{T_{hwy}} w(t)$$

- A Matlab code has been written that allows the user to input various vehicle parameters to calibrate the model coefficients.

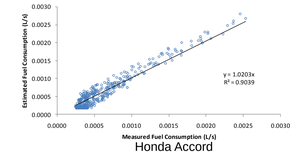


MATLAB CPFM Calibration Tool

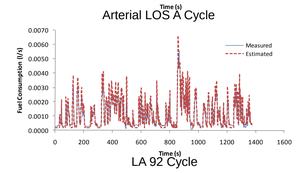
Model Validations



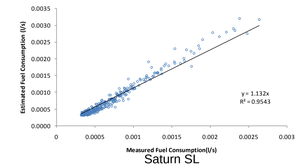
Arterial LOS A Cycle



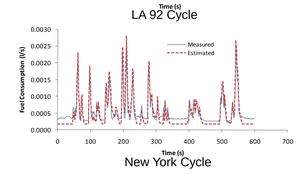
Honda Accord



LA 92 Cycle



Saturn SL



New York Cycle

Instantaneous Model Estimation

Model Validation, New York City Cycle

Conclusions

- The models are demonstrated to estimate vehicle fuel consumption rates consistent with in-field measurements (coefficient of determination above 0.90).
- The development of this model attempts to bridge the existing gap between traditional power-based fuel consumption models and vehicle operational control systems such as fuel-optimized cruise control systems, real-time eco-driving systems, and adaptive cruise control systems on passenger cars using road topography information.

Acknowledgments

The authors acknowledge the financial support from NAVTEQ Corporation under Contract NTCRP-0000055801. The authors also acknowledge the input and feedback received from NAVTEQ Corporation.