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Development of a transient fuel consumption model

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ABSTRACT

Most existing fuel consumption models are based on steady-state fuel mapping. However, these models cannot provide satisfactory predictions for vehicles operating under transient conditions. Consequently, a new transient model that can precisely predict fuel consumption under steady-state and transient conditions was developed on the basis of the steady-state model. This new model is characterised by two sub-modules: the steady-state module whose inputs are engine speed and torque, and the transient correction module whose inputs are vehicle speed and acceleration. Vehicle Specific Power (*VSP*) was introduced as a filter to help develop different correction factors for positive and negative *VSP*. The Argonne National Laboratory's measurements of different driving cycles including the steady-state cycle, the UDDS cycle, the Highway cycle and the US06 cycle were used to develop the new model. According to the results of this study, the prediction accuracy of fuel consumption models can be improved significantly by introducing transient corrections. The Mean Absolute Percentage Error (*MAPE*) between the predicted and measured fuel consumption decreased from approximately 58% for the steady-state model alone to approximately 23.5% when the transient correction module was introduced. Moreover, this new model performs better than the VT-Micro model. The *MAPE* values of the new transient models were approximately 2.7–4.6% lower than that of the VT-Micro model.

1. Introduction

Transportation is the largest oil consumer and the second largest source of carbon dioxide emissions in the world. In 2011, approximately 59% of oil was used for transportation (World Oil Outlook, 2014) and approximately 22% of carbon dioxide emissions resulted from transportation (IEA, 2013). Energy and environmental issues resulting from transportation are becoming increasingly serious. It is extremely important to develop effective eco-planning systems, such as intelligent transportation systems (ITSs), eco-driving assist systems and eco-routing assist systems, to help control and reduce fuel consumption. To better evaluate these eco-driving and eco-routing systems, a model that can precisely predict fuel consumption second by second is necessary.

Existing fuel consumption models can be classified as steady-state and transient fuel consumption models based on their accuracy when predicting fuel consumption under transient conditions. Current state-of-the-art steady-state fuel consumption models predict fuel consumption based on steady-state dynamometer experimental data. Generally, steady-state fuel maps or the polynomials of engine speed and torque are used to predict vehicle fuel consumption under different operation conditions. Typical steady-state models include the power-based model proposed by Post et al. (1984) the torque-based

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model proposed by Passenberg et al. (2009) and the engine-load-based model proposed by Bart Saerens et al. (2013). Although this approach gives a satisfactory prediction of fuel consumption under steady-state conditions, large discrepancies are observed when vehicles operate under transient conditions (Chiara et al., 2011).

Transient models can be used to precisely estimate vehicle fuel consumption under steady-state and transient conditions. However, few transient fuel consumption models are found in the literature. Lindgren proposed a calculation model for non-road mobile machinery that accounts for the effects of transient conditions on the overall fuel consumption (Lindgren, 2005). The model included static effects and correction factors accounting for engine speed and torque transients. In the static part, fuel consumption was calculated as if the transient effects were neglected. In the transient correction part, the correction factors were calculated through the transients in engine speed and engine torque, firstly independent of each other and then as a synergism. A similar approach was used Chiara et al. (2011), who developed a transient model for diesel engines based on engine control. The model accounted for the interaction between prediction of key engine signals and the control actions dictated by the engine control unit (ECU) algorithms. A start-up correction and a fuel-to-air ratio limitation correction were used to correct the map-based steady-state prediction. But the variables they used, such as the transient air mass flow rate, were not always available for most modelers. Pelkmans et al. developed a vehicle-level simulation tool called VeTESS that can be used to calculate fuel consumption of vehicles operated under dynamic conditions within the European project Decade (Pelkmans et al., 2004). VeTESS adopted a quasi-steady-state modelling approach, it accounted for the dynamic behavior of the engine by introducing the transient in engine torque based on a steady-state fuelling map. Rakha and Ahn et al. developed the VT-Micro model to predict the fuel consumption of light-duty vehicles under warmed-up conditions based on their instantaneous speed and acceleration (Ahn et al., 2002). The model coefficients for acceleration and deceleration modes were determined separately to account for the differences in fuel consumption rate sensitivity to speed. Natural logarithms were also used to ensure that non-negative fuel consumption rates were produced. The same model structure was also adopted by Wei Lei et al. they combined the polynomial model with the VT-Micro model and proposed the Microscopic Emission and Fuel consumption (MEF) model (Wei et al., 2010). The instantaneous acceleration in VT-Micro model was replaced with a composite acceleration, which enabled the MEF to account for the effect of history acceleration on fuel consumption.

The difference in fuel consumption between steady-state and transient conditions can be substantial (Hansson et al., 2003). Several studies have shown that fuel consumption under transient conditions can be 6% to 30% greater than fuel consumption under steady-state conditions (Chiara et al., 2011; Lindgren, 2005; Pelkmans et al., 2004; Hansson et al., 2003; Lindgren and Hansson, 2004; Callahan et al., 1985). Therefore, transient fuel consumption models are necessary to precisely evaluate the performance of eco-driving and eco-routing systems. Fuel consumption models that were used in eco-driving and eco-routing systems should be simple and accurate enough. However, some drawbacks exist in the aforementioned transient models. The models in Chiara et al. (2011), Lindgren (2005) and Pelkmans et al. (2004) used transient corrections to improve model accuracy, but the variables they used, such as the transients in engine speed and torque, the transient air mass flow rate, are difficult to measure. The VT-Micro model and the MEF model cannot distinguish whether the vehicle is on a sloped road or a level road given the same speed and acceleration. These drawbacks limited these transient models from being used in eco-driving and eco-routing systems. Therefore, the purpose of this work is to establish a transient model that is suitable for eco-driving and eco-routing systems.

2. Modelling methodology

Currently, the methods for developing transient fuel consumption models can be divided into the following two categories: (i) transient-correction-based modelling, which introduces transient corrections based on steady-state predictions and (ii) direct dynamic-variables-based modelling, which develops transient models by directly using dynamic variables. Dynamic variables mainly refer to variables that can describe vehicle dynamics. Table 1 shows the typical transient models and corresponding dynamic variables of each modelling method.where "Engine fuel Map" represents the traditional engine fuel map; $\dot{m}_{air}$ (g/s) is the transient air mass flow rate; ΔT (N m/s) and $\Delta\omega$ (rad/s^2) are the transients in engine torque and speed, respectively; MOE_e is instantaneous fuel consumption rate (mg/s); $L_{i,j}$ (–) and $M_{i,j}$ (–) are the model regression coefficients; s (km/h) and a (m/s^2) are the vehicle instantaneous speed and acceleration, respectively; $\bar{a}(t)$ (m/s^2) is the composite acceleration at time t (s); α (–) is the acceleration impact factor; Chiara et al. (2011), Lindgren (2005), Pelkmans et al. (2004),

Table 1
Dynamic variables in the transient models.

Modelling method	Transient model	Dynamic variables
Transient- correction- based	Engine fuel Map + start-up & fuel-to-air ratio limitation correction (Chiara et al., 2011)	$\dot{m}_{air}$
	Engine fuel Map + engine speed and torque change correction (Lindgren, 2005)	$\Delta T, \Delta\omega$
	Engine fuel Map + torque change correction (Pelkmans et al., 2004)	ΔT
Direct dynamic- variable- based	$\ln(MOE_e) = \sum_{i=0}^{3}\sum_{j=0}^{3}(L_{i,j}s^i a^j)a \geqslant 0$, $\ln(MOE_e) = \sum_{i=0}^{3}\sum_{j=0}^{3}(M_{i,j}s^i a^j)a < 0$ (Ahn et al., 2002)	a
	$\ln(MOE_e) = \sum_{i=0}^{3}\sum_{j=0}^{3}(L_{i,j}s^i \bar{a}^j)\bar{a} \geqslant 0$ $\ln(MOE_e) = \sum_{i=0}^{3}\sum_{j=0}^{3}(L_{i,j}s^i \bar{a}^j)\bar{a} \geqslant 0$ $\bar{a}(t) = \alpha \cdot a(t) + (1-\alpha)\sum_{i=1}^{9}a(t-i)/9$ (Wei et al., 2010)	$\bar{a}$