SAE TECHNICAL
PAPER SERIES

981902

Critical Issues in Quantifying Hybrid Electric Vehicle Emissions and Fuel Consumption

Feng An and Matthew Barth
University of California

The Engineering Society
For Advancing Mobility
Land Sea Air and Space®
INTERNATIONAL

Future Transportation Technology
Conference & Exposition
Costa Mesa, CA
August 11-13, 1998

The appearance of this ISSN code at the bottom of this page indicates SAE's consent that copies of the paper may be made for personal or internal use of specific clients. This consent is given on the condition, however, that the copier pay a $7.00 per article copy fee through the Copyright Clearance Center, Inc. Operations Center, 222 Rosewood Drive, Danvers, MA 01923 for copying beyond that permitted by Sections 107 or 108 of the U.S. Copyright Law. This consent does not extend to other kinds of copying such as copying for general distribution, for advertising or promotional purposes, for creating new collective works, or for resale.

SAE routinely stocks printed papers for a period of three years following date of publication. Direct your orders to SAE Customer Sales and Satisfaction Department.

Quantity reprint rates can be obtained from the Customer Sales and Satisfaction Department.

To request permission to reprint a technical paper or permission to use copyrighted SAE publications in other works, contact the SAE Publications Group.

GLOBAL MOBILITY DATABASE

All SAE papers, standards, and selected books are abstracted and indexed in the Global Mobility Database

No part of this publication may be reproduced in any form, in an electronic retrieval system or otherwise, without the prior written permission of the publisher.

ISSN 0148-7191
Copyright 1998 Society of Automotive Engineers, Inc.

Positions and opinions advanced in this paper are those of the author(s) and not necessarily those of SAE. The author is solely responsible for the content of the paper. A process is available by which discussions will be printed with the paper if it is published in SAE Transactions. For permission to publish this paper in full or in part, contact the SAE Publications Group.

Persons wishing to submit papers to be considered for presentation or publication through SAE should send the manuscript or a 300 word abstract of a proposed manuscript to: Secretary, Engineering Meetings Board, SAE.

Printed in USA

DOCKET ALARM

Find authenticated court documents without watermarks at docketalarm.com.

981902

Critical Issues in Quantifying Hybrid Electric Vehicle Emissions and Fuel Consumption

Feng An and Matthew Barth
University of California

ABSTRACT

Quantifying Hybrid Electric Vehicle (HEV) emissions and fuel consumption is a difficult problem for a number of different reasons: 1) HEVs can be configured in significantly different ways (e.g., series or parallel); 2) the Auxiliary Power Unit (APU) can consist of a wide variety of engines, fuel types, and sizes; and 3) the APU can be operated very differently depending on the energy management system strategy and the type of driving that is performed (e.g., city vs. highway driving).

With the future increase of HEV penetration in the vehicle fleet, there is an important need for government agencies and manufacturers to determine HEV emissions and fuel consumption. In this paper, several critical issues associated with HEV emissions and fuel consumption are identified and analyzed, using a sophisticated set of HEV and emission simulation modeling tools. Two different types of APUs are modeled, one based on a conventional gasoline Internal Combustion Engine (ICE), the other based on a small hydrogen-fueled ICE. Different energy management strategies and HEV configurations are examined, including a parallel range-extender charge-depleting HEV, a series thermostatic charge-sustaining hydrogen HEV truck, and a power-splitting charge-sustaining HEV (modeled after the Toyota Prius). Results show that HEV emissions and energy consumption have a high degree of dependency on: 1) the energy management strategy employed; 2) the length of the drive cycle; 3) overall driving range; and 4) the initial battery state-of-charge (SOC). The simulation results present: 1) equivalent fuel economy; 2) emissions per mile; 3) pure electric range; and 4) total driving range, for the different cases analyzed. The simulation modeling tools are extremely useful for comparing different HEV configurations and should play an important role in developing a robust HEV emissions and fuel consumption test procedure.

INTRODUCTION

All hybrid-electric vehicles include three key components - an on-board auxiliary power unit (APU), an energy storage system and a control system which carries out a particular energy management strategy. These three components can be highly variable from vehicle to vehicle and can have a profound effect on an HEV's energy and emission performance. In this paper, we attempt to identify some of the key variables that have a significant effect on an HEV's energy and emissions. Various HEV configurations, APU types, and control strategies are simulated and analyzed as examples to illustrate the energy and emission impacts.

Specifically, an electric vehicle and three different hybrid electric vehicles are simulated using five different kinds of driving patterns (embodied as driving cycles). These modeled vehicles include: 1) a GM EV_1 with NiMH batteries; 2) a parallel-configured UC-Davis-type range-extender charge-depleting HEV; 3) a series-configured charge-sustaining hydrogen-fueled HEV truck; and 4) a power splitting continuous-variable-transmission (CVT) HEV similar to the Toyota Prius. Further, a conventional vehicle (a 96 Toyota Corolla) is also simulated to serve as a baseline. The five driving cycles applied to the simulation models include: 1) EPA's Highway Cycle (HWY); 2) EPA's City Cycle (LA4); 3) California Air Resources Board (CARB) Unified LA 92 Cycle (LA92); 4) the New York City Cycle (NYC); and 5) the US06 Cycle (US06).

Previous research has shown that conventional ICE vehicle tailpipe emissions and fuel economy are extremely sensitive to different driving cycles [1-7]. For example, a Ford Taurus tested using the LA4 cycle achieves approximately 20 miles per gallon (MPG). By contrast, when applying the NYC cycle [1, 2] (which represents driving in congested urban conditions), the fuel economy drops to approximately 10 MPG [1]. Tailpipe emissions of pollutants including carbon monoxide (CO), hydrocarbons (HC), and oxides of nitrogen (NOx) also change dramatically with different driving conditions. Recent studies indicate that CO and HC emissions under aggressive driving conditions can be several orders of magnitude greater than when tested under LA4 certified conditions [8-11].

Recent electric vehicle (EV) studies and tests also indicate that their range and efficiency depend greatly on operating conditions [12-14]. The "real-world" driving advertised (based on the standard testing procedure), because “real world” driving patterns may include higher or lower speeds, more aggressive acceleration rates, and more stop-and-go type of driving.

The estimation of an HEV’s energy use and emissions is more difficult, since HEVs can consist of a wide spectrum of vehicle classes, e.g., from a “range extender” to a “power assist”-type of vehicle (see, e.g., [15]). The variables associated with an HEV design can be arranged and sized to meet different design objectives [15, 16]. This design variability creates additional challenges when evaluating an HEV’s performance.

MODELING APU EMISSIONS

In this research, two different APU modeling methodologies are used. A hydrogen-fueled ICE is modeled using a steady-state emissions map approach. In contrast, a gasoline-fueled APU is modeled based on a modal emissions model developed for a conventional vehicle. Advantages and disadvantages of these two approaches have been discussed in another paper [4]. Essentially, the second modeling approach is more comprehensive, but requires more detailed measurement data. The engine-map approach is easier to implement, but is less accurate. These methodologies are described further below.

HYDROGEN-FUELED ICE APU EMISSIONS MODEL – One of the simplest approaches to modeling an ICE’s energy consumption and emissions is based on measuring fuel consumption and emissions at steady-state loads and engine speeds, and creating what are called “engine maps”. These engine maps are essentially look-up tables with fuel consumption and emissions indexed as a function of engine speed (RPM) and engine torque demand.

When modeling a vehicle’s fuel consumption and emissions, it is necessary to first convert second-by-second vehicle velocity (and acceleration) into power demand, which then must be translated into second-by-second engine speed and torque demand. The engine maps can then be applied, giving the energy consumption and emissions by interpolating over the maps. This modeling methodology works well over slowly changing velocities, however it potentially can miss transient emissions that may occur during transitions from different steady-state levels.

For our example vehicle, a brake specific fuel consumption (*bsfc*) map and a NOx emission map for the hydrogen-fueled APU were created using on steady-state engine emission tests. In Table 1, RPM is engine speed in revolution per minute, torque is in lb-ft, and *bsfc* is in lb/hp-hr. In Table 2, NOx is in grams/second.

The biggest advantage of the engine map approach is its simplicity. The major disadvantage is that it is based on steady-state measurements, thus may not accurately

strategies where the APU is operated at a fixed torque-rpm point (e.g., a “thermostatic” control strategy), transient emissions do not occur and are thus not a major concern.

Table 1. Hydrogen Engine Fuel Consumption Map (*bsfc* vs. rpm & torque)

RPM\Torq.	10	20	30	40	50	60
1000	0.2880	0.1730	0.1620	0.1600	0.1600	0.1600
1500	0.2880	0.1770	0.1590	0.1510	0.1590	0.1730
2000	0.2880	0.2140	0.2000	0.1877	0.1850	0.1990
2500	0.2880	0.2520	0.2180	0.2000	0.1987	0.2185
3000	0.2880	0.2675	0.2285	0.2090	0.2185	0.2800
3500	0.2880	0.2800	0.2600	0.2800	0.2800	0.2800

Table 2. Hydrogen Engine NOx Emission Map (grams/second vs. rpm & torque)

RPM\Torq.	10	20	30	40	50	60
1000	0.0003	0.0003	0.0003	0.0004	0.0014	0.0068
1500	0.0003	0.0003	0.0003	0.0004	0.0014	0.0068
2000	0.0003	0.0003	0.0005	0.0009	0.0017	0.0061
2500	0.0005	0.0004	0.0006	0.0010	0.0037	0.0086
3000	0.0006	0.0007	0.0008	0.0018	0.0086	0.0130
3500	0.0007	0.0009	0.0015	0.0028	0.0130	0.0173

Based on Table 1, the operational point with the lowest *bsfc* value (0.151 lb/hp-hr) is at torque 40 lb-ft @ 1500 rpm. The corresponding NOx emission rate is 0.0004 g/s. This point is often referred to as the “sweet spot”. It is important to note that this sweet spot doesn’t correspond to the lowest emission rate, which is 0.0003 g/s based on Table 2. Ideally, one would like to operate the engine at its sweet spot which corresponds to both the lowest fuel consumption value and emission rate. In this case, however, it would mean operating the engine at 40*1500/5252 = 11.4 hp, which is only about 1/3 of its rated power, which is unacceptable. In terms of functionality, many control strategies want to operate near the designed maximum power point. For this modeled hydrogen-fueled ICE, this corresponds to 50 lb-ft@3000 rpm, which is equivalent to 50*3000/5252 = 28.6 hp. This point corresponds to a *bsfc* value of 0.2185 lb/hp-hr, and a NOx emission rate of 0.0086 g/s. A more detailed discussion of the thermostat control strategy can be found in a later section of this paper.

GASOLINE-FUELED ICE APU EMISSIONS MODEL – An alternative to the engine-map approach is developing a true “modal” emission model. A modal emission model predicts emissions (and fuel consumption) based on vehicle operating *mode*, e.g., idle, steady-state cruise, various levels of acceleration/deceleration, etc. A major advantage of modal emissions modeling approach is that important for some HEV configurations, such as a parallel-configured HEV which allows its APU to be engaged in load-following driving, where transient driving events have direct impact on APU operation. The disadvantage of the modal emissions model approach is that it requires much more detailed testing data.

Using this modal emissions modeling approach, vehicle tailpipe emissions are modeled on a second-by-second basis as the product of three components: fuel rate (FR), engine-out emission indices (gemission/gfuel), and catalyst pass fraction (CPF) [6, 8, 17]:

$$\text{tailpipe emissions} = FR \bullet \left(\frac{g_{\text{emission}}}{g_{\text{fuel}}}\right) \bullet CPF \qquad \text{(Eq. 1)}$$

Here FR is fuel use rate in grams/s, engine-out emission index is grams of engine-out emissions per gram of fuel consumed, and CPF is the catalyst pass fraction, defined as the ratio of tailpipe to engine-out emissions.

The general structure of the modal emissions model is composed of six modules, as illustrated by the six rectangular boxes in Figure 1: 1) engine power demand; 2) engine speed; 3) air/fuel ratio; 4) fuel-rate; 5) engine-out emissions; and 6) catalyst pass fraction. The model as a whole requires two groups of inputs (rounded boxes in Figure 1): A) input operating variables, such as the second-by-second speed trace; and B) model parameters, such as vehicle mass and engine size. The output of the model is tailpipe emissions and fuel consumption.

There are four operating conditions in the model (ovals in Figure 1): a) cold start; b) stoichiometric; c) enrichment; and d) lean burn. Hot-stabilized vehicle operation encompasses conditions b) through d); the model determines which condition the vehicle is operating at a given moment by evaluating vehicle power demand. For example, when the vehicle power demand exceeds a power enrichment threshold, the operating condition switches from stoichiometric to enrichment conditions. The model does not inherently determine when a cold start occurs; rather, the user must specify any cold start conditions. The model does determine when the operating condition switches from cold start to stoichiometric, however.

The vehicle power demand (1) is determined based on operating variables (A) and specific vehicle parameters (B). All other modules require the input of additional vehicle parameters determined based on dynamometer measurements, as well as the engine power demand calculated by the model.

The air/fuel equivalence ratio (which is the ratio of stoichiometric air/fuel ratio, roughly 14.6 for gasoline, to the instantaneous air/fuel ratio), ϕ, is approximated only as a function of power, and is modeled separately in each of the four operating conditions a) through d). The core of the model is the fuel rate calculation (4). It is a function of power demand (1), engine speed (2), and air/fuel ratio (3). Engine speed is determined based on vehicle veloc-

detailed discussion on this modal emission modeling approach is given in [18].

One of the advantages of the modal emissions modeling approach for evaluating HEV ICEs is that we can appropriately "downsize" established models that were developed from extensive testing from a parallel research program. Several parameters from the established models (such as engine displacement, emission indices, etc.) were reduced to give fuel and emission responses typical of a smaller sized engine that might be employed as and HEV's APU.

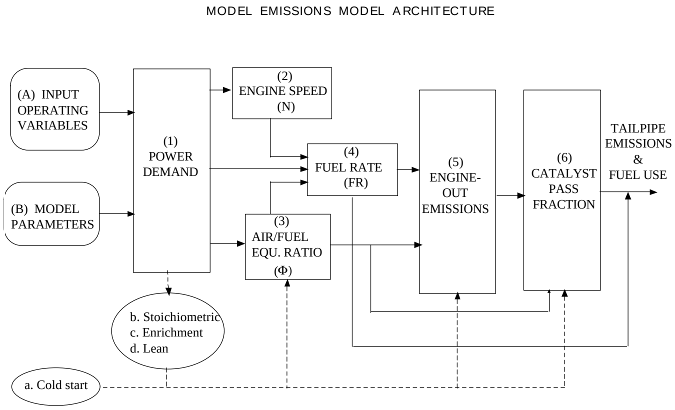

Figure 1. Modal Emissions Model Architecture.

ELECTRIC POWERTRAIN SIMULATION MODEL

In order to estimate key characteristics of both EVs and HEVs, an electric powertrain simulation model has been developed (after [19]). The approach used relies on a few simplified analytic formulas and some key physical parameters. The flowchart of the electric powertrain is illustrated in Figure 2. There are four key components in an electric powertrain:

1. a tractive power demand module which converts second-by-second vehicle velocity to power demand required at the wheels (or tractive power $P_{tractive}$);
2. a drivetrain module which converts second-by-second tractive power $P_{tractive}$ into second-by-second required motor torque (Tor_{motor}) and required motor speed (rpm_{motor});
3. a motor/controller module which converts motor torque and speed into power required from the battery terminal (P_{batt});
4. a battery simulation module which calculates second-by-second current, voltage, and battery state-of-charge (SOC). Some of the key characteristics that are calculated include total energy used per distance (i.e., *kWh/mi*), electric *range* of the vehicle given battery capacity, equivalent fuel economy, which also factors in power plant efficiency (i.e., MPG_{equiv}), and overall battery efficiency.

The input requirements for this simulation model (shown as rounded boxes in Figure 2) are categorized into four

DOCKET ALARM

Explore Litigation Insights

Docket Alarm provides insights to develop a more informed litigation strategy and the peace of mind of knowing you're on top of things.

Real-Time Litigation Alerts

Keep your litigation team up-to-date with **real-time alerts** and advanced team management tools built for the enterprise, all while greatly reducing PACER spend.

Our comprehensive service means we can handle Federal, State, and Administrative courts across the country.

Advanced Docket Research

With over 230 million records, Docket Alarm's cloud-native docket research platform finds what other services can't. Coverage includes Federal, State, plus PTAB, TTAB, ITC and NLRB decisions, all in one place.

Identify arguments that have been successful in the past with full text, pinpoint searching. Link to case law cited within any court document via Fastcase.

Analytics At Your Fingertips

Learn what happened the last time a particular judge, opposing counsel or company faced cases similar to yours.

Advanced out-of-the-box PTAB and TTAB analytics are always at your fingertips.

API

Docket Alarm offers a powerful API (application programming interface) to developers that want to integrate case filings into their apps.

LAW FIRMS

Build custom dashboards for your attorneys and clients with live data direct from the court.

Automate many repetitive legal tasks like conflict checks, document management, and marketing.

FINANCIAL INSTITUTIONS

Litigation and bankruptcy checks for companies and debtors.

E-DISCOVERY AND LEGAL VENDORS

Sync your system to PACER to automate legal marketing.

WHAT WILL YOU BUILD? | **sales@docketalarm.com** | **1-866-77-FASTCASE**

fastcase®
Smarter legal research.