SAE TECHNICAL PAPER SERIES

970289

Analysis of the Fuel Economy Benefit of Drivetrain Hybridization

Matthew R. Cuddy and Keith B. Wipke
National Renewable Energy Lab

Reprinted from: Electric and Hybrid Vehicle Design Studies (SP-1243)

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

International Congress & Exposition
Detroit, Michigan
February 24-27, 1997

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 SAE Global Mobility Database.

ISSN 0148-7191

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

970289

Analysis of the Fuel Economy Benefit of Drivetrain Hybridization

Matthew R. Cuddy and Keith B. Wipke
National Renewable Energy Lab

ABSTRACT

Parallel- and series-configured hybrid vehicles likely feasible in next decade are defined and evaluated using NREL's flexible ADvanced VehIcle SimulatOR, ADVISOR. Fuel economies of these two diesel-powered hybrid vehicles are compared to a comparable-technology diesel-powered internal-combustion-engine vehicle. Sensitivities of these fuel economies to various vehicle and component parameters are determined and differences among them are explained. The fuel economy of the parallel hybrid defined here is 24% better than the internal-combustion-engine vehicle and 4% better than the series hybrid.

INTRODUCTION

Automobile drivetrain hybridization (using two types of energy converters rather than just one, as conventional-drivetrain vehicles do) is considered an important step to high fuel economy. The Department of Energy has established cost-shared programs with Chrysler, Ford, and General Motors under the Hybrid Vehicle Propulsion System Program to double the fuel economy of midsized automobiles, without sacrificing performance and consumer acceptability, by hybridizing their drivetrains. The government/industry Partnership for the New Generation of Vehicles (PNGV) effort has also identified hybridization as an important step toward tripling mid-sized sedan fuel economy. Recent and ongoing work seeks both to identify the likely fuel economy gains hybrid vehicles can deliver, and to ascertain the hybrid configuration that will lead to the best fuel economy [1-6].

Tamor, of Ford Motor Co., uses energy throughput spectra of current internal-combustion-engine vehicles (ICEVs) along with Ford Ecostar electric-drive data and an idealized battery model to estimate the greatest possible benefit of drivetrain hybridization to be 50% [6]. Given a 100% efficient energy storage system and ideal control stragegy, Tamor estimates a parallel hybrid will have a combined federal fuel economy of roughly 1.5 times the fuel (Combined federal fuel economy is computed assuming 55% of miles are driven on the USEPA Federal Urban Drive Schedule (FUDS) and 45% on the USEPA Federal Highway Drive Schedule (FHDS).) Further, Tamor concludes that engine and road loads being equal, a parallel hybrid is more fuel-efficient than a series hybrid. Mason and Kristiansson, however, assert that series hybrids are likely to be more fuel-efficient than parallel hybrids [7]. Initial studies at NREL using current and projected component data indicated that series and parallel hybrids have similar fuel economy potential [8].

This analysis predicts the fuel economy differences among a series hybrid, a parallel hybrid, and an ICEV of similar levels of advancement and performance, using component and vehicle data adapted from current technologies. The methods of analysis and assumptions required are presented. The dependence of the fuel economy of each vehicle upon the assumptions are presented, allowing an understanding of the various projections of hybrid fuel economy made in the literature. Sensitivity coefficients, required for the fuel economy sensitivity analysis and analogous to the "influence coefficients" discussed by Sovran and Bohn are also presented [9]. These sensitivity coefficients may be used to estimate the fuel economy of derivatives of the vehicles presented.

The National Renewable Energy Laboratory's (NREL's) ADvanced VehIcle SimulatOR (ADVISOR), was used along with data from the literature and from industry contacts to define and evaluate charge-sustaining hybrids (which may operate without wall-charging, as long as there is fuel in their tank) and a ICEV for comparison. ADVISOR was also used to determine numerically the sensitivity of each vehicle's fuel economy to changes in vehicle and component parameters. These sensitivities were then used to analyze the predicted fuel economy differences among the three vehicles.

The only vehicle figure of merit being considered here is fuel economy. We recognize that there are many other vehicle such as cost, reliability, and emissions. Our focus here, however, is solely on the likely potential to improve fuel economy by drivetrain hybridization. With that focus, we found the series hybrid defined here is 18% more fuel-efficient than the ICEV and the parallel hybrid is 24% more fuel-efficient than the ICEV. A 10% drop in battery turnaround efficiency (from ~88% to ~80%) causes a 1.5% drop in series hybrid fuel economy (for this particular control strategy) and a 1.3% drop in parallel hybrid fuel economy. The sensitivity to regenerative braking effectiveness is likewise small: a 10% drop in regenerative braking effectiveness causes a 0.7% drop in parallel hybrid fuel economy and a 1.0% drop in series hybrid fuel economy.

BASELINE VEHICLES

The vehicles used in this study were defined using current and projected vehicle and component data. Using NREL's vehicle performance simulator, ADVISOR, (which has been benchmarked against industry simulation tools,) the components were sized to meet performance goals, and transmission and hybrid control strategies were optimized for fuel economy subject to performance constraints. ADVISOR was then used to evaluate the vehicles' fuel economy. The vehicles in this study are shown schematically in Figure 1.

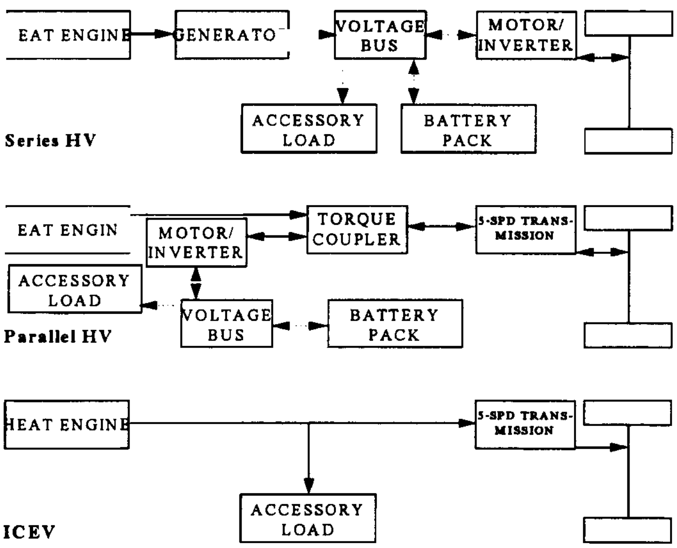

Figure 1. Energy-flow schematics of the series hybrid (top), parallel hybrid (middle), and ICEV (bottom). Solid lines indicate mechanical energy, and dashed lines indicate electrical energy.

VEHICLE SPECIFICATION

Component Specification - Table 1 lists the main component efficiencies and road load parameters assumed for this effort.

The heat engine used here is a direct-injection (DI) diesel, with a fuel-use map from the 5-cylinder, 85 kW Audi engine [10], scaled to peak efficiencies given in Table 1. See the "Scaling" section below for discussion of efficiency-versus-size-and-year considerations. The generator coupled to the diesel in the series hybrid vehicle (HV) is based on a permanent magnet motor/controller set from Unique

based on the AC induction system being developed by Westinghouse. The batteries modeled here are advanced lead-acid, with characteristics adapted from Optima [11]. Vehicle drag parameters were chosen to define a Partnership for the New Generation of Vehicles (PNGV)-like vehicle with an aluminum-intensive body, heavy by Moore's standards but deemed achievable by those in industry interviewed by Duleep [2,4]. The "regenerative braking fraction" in the table is defined here as the fraction of braking energy during a given cycle that is provided to the electric drivesystem, with the balance, 60% in this case, handled by friction brakes.

Table 1. Vehicle summary data

Parameter	Series HV	Parallel HV	ICEV
Heat Engine			
type	DI Diesel	DI Diesel	DI Diesel
maximum power	32 kW	35 kW	62 kW
specific power	500 W/kg [13]	500 W/kg [13]	500 W/kg [13]
peak efficiency	43% [10]	43% [10]	46.5% [13]
avg. efficiency	40.2%	36.4%	26.0%
Generator			
type	Permanent Magnet	--	--
maximum power	32 kW	--	--
specific power	840 W/kg [14]	--	--
peak efficiency	95% [14]	--	--
avg. efficiency	90% [14]	--	--
Motor/Inverter			
type	AC induction	AC induction	--
max. continuous power	53 kW	27 kW	--
specific power	820 W/kg [15]	820 W/kg [15]	--
peak efficiency	92% [15]	92% [15]	--
avg. efficiency	86.8%	89.4%	--
Battery Pack			
type	Advanced Lead-Acid	Advanced Lead-Acid	--
maximum power	63 kW	32 kW	--
specific power @ 50% SOC (including enclosure and thermal management)	800 W/kg	800 W/kg	--
capacity	2.4 kWh	1.2 kWh	--
avg. round-trip efficiency	87.6%	87.7%	--
Transmission			
type	1-spd	man. 5-spd	man. 5-spd
avg. efficiency	98% [16]	92% [16]	92% [16]
Vehicle			
C_DA	0.4 m² [12]	0.4 m² [12]	0.4 m² [12]
$C_{rolling\text{-}resistance}$	0.008	0.008	0.008
accessory load	800 Welec	800 Welec	800 Wmech
regenerative braking fraction	0.4	0.4	0.4
5-6 pass. glider mass	840 kg [4]	840 kg [4]	840 kg [4]
passenger/cargo mass	136 kg	136 kg	136 kg
test mass (including driver/	1243 kg	1218 kg	1214 kg

Table 1 also indicates propulsion component size and average energy efficiency over the combined federal cycle. Propulsion system components for each of the three vehicles were sized, using ADVISOR, in order to meet performance requirements set out by the US Consortium for Automotive Research (USCAR) for the PNGV effort [12]:

1. 0 to 96.5 km/h (0 to 60 MPH) in 12 s
2. 64.4 to 96.5 km/h (40 to 60 MPH) in 5.3 s
3. 0 to 136.8 km/h (0 to 85 MPH) in 23.4 s, and
4. 6.5% gradeability at 88.5 km/h (55 MPH).

The PNGV targets listed as 1-3 above must be attained at curb weight plus 136 kg for the driver and passenger, while the gradeability requirement is prescribed at gross vehicle weight with full accessory load for 20 minutes. We have differed from the PNGV specifications in that the gradeability requirement placed on the vehicles in this study is 6.5% at 88.5 km/h indefinitely (until the fuel runs out), with average accessory load, at curb weight plus 136 kg.

The HPU size for the hybrids is determined by the continuous gradeability requirement. Note that the HPU for the series HV is smaller than for the lighter parallel HV. This is because the 88.5 km/h requirement, for a given gear ratio, requires the parallel HV's HPU to provide adequate climbing power at a certain speed which, in this case, is not the speed at which it develops maximum power. The series HV's HPU may operate at maximum power regardless of the vehicle speed; thus, its maximum power can be set to exactly the climbing power requirement. With the HPU sized for both vehicles, the motor and batteries are sized to meet the acceleration requirements, numbered one through three above.

Scaling - In this study, the efficiency map for an 85-kW engine introduced in 1990 is used to describe the behavior of 32-, 35- and 62-kW engines [10]. For the 32- and 35-kW engines, the original map shape and peak efficiency value were maintained, while the torque axis was compressed. We acknowledge the significant technical challenge involved in achieving such high peak efficiencies with a small engine, but are encouraged by continued progress by VW/Audi (which introduced a 66 kW DI diesel with 41.8% peak efficiency two years after the 85 kW benchmark) [17]. We believe 43% peak efficiency in 32- to 35-kW diesel engines in 2005 is consistent with the Office of Advanced Automotive Technology's 2004 target of 45% peak efficiency for 40- to 55-kW engines, which is a goal at least some diesel manufacturers find reasonable [13,18]. We have assumed a peak efficiency of 46.5%, the peak efficiency of current state-of-the-art heavy-duty diesel engines, for the 62-kW engine in 2005, with its higher peak efficiency due to its larger size [13]. We expect the smaller (HV) engines to have lower specific power; the effect of changes in engine specific power can be derived using the data in Table 5.

The tractive motors in this study, at outputs of 53

from which their maps come. However, motors of these lower power levels with peak efficiencies of over 92% are available now [14]. We have not attempted to scale the efficiencies up, as would likely result from further development, for lack of data.

Series Hybrid Control Strategy - The strategy chosen here was a close-power-follower strategy where the hybrid power unit (HPU) power output closely follows the tractive motor output. Figure 2 shows the behavior of the vehicle propulsion system following this strategy over the first 315 s of the FUDS. The HPU power (represented by the dots) varies directly with the tractive motor power (represented by a solid line), but is higher by a state-of-charge-dependent factor to allow for losses in the generator and battery. In this strategy, the HPU power is given by (K1*(tractive_motor_power) + K2)*(SOChi-SOC)/(SOChi-SOClo), where SOChi and SOClo are threshold SOCs.

As the third chart in the figure indicates, this control strategy leads to nearly constant battery pack state-of-charge (SOC). (See the "Results and Discussion" section for a more detailed discussion of the control strategies considered here.)

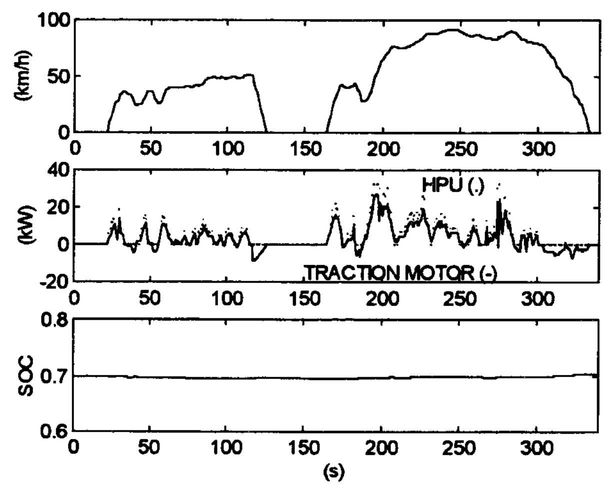

Figure 2. Close-Follower Control Strategy

We have chosen a power-follower strategy where the HPU power follows the motor power's second-by-second variation, which defines a vehicle that achieves 29.5 km/L (69.4 MPG) on the combined federal drive schedule. This strategy was chosen because:

1) it leads to the best fuel economy in the control strategy design space of power-follower approaches considered here, and

2) it requires the HPU to immediately follow tractive power requirements, as occurs in the parallel hybrid and ICEVs. This leads the fuel economy estimate of each vehicle to be overestimated roughly equally due to the consistent neglect of transient effects, minimizing the effect of transient fuel use on the differences among the three vehicles' fuel economy.

This approach likely has no emissions benefit over ICEVs and is chosen only for its fuel economy

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 inter-face) 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.