SAE TECHNICAL PAPER SERIES

2006-01-0442

Simulation of an Integrated Starter Alternator (ISA) System for the HMMWV

Andreas Malikopoulos, Zoran Filipi and Dennis Assanis
Automotive Research Center, The University of Michigan

Reprinted From: Advanced Hybrid Vehicle Powertrains 2006 (SP-2008)

ISBN 0-7680-1718-1

9 780768 017182

2006 SAE World Congress
Detroit, Michigan
April 3-6, 2006

SAE International™

400 Commonwealth Drive, Warrendale, PA 15096-0001 U.S.A. Tel: (724) 776-4841 Fax: (724) 776-5760 Web: www.sae.org

The Engineering Meetings Board has approved this paper for publication. It has successfully completed SAE's peer review process under the supervision of the session organizer. This process requires a minimum of three (3) reviews by industry experts.

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.

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

Printed in USA

2006-01-0442

Simulation of an Integrated Starter Alternator (ISA) System for the HMMWV

Andreas Malikopoulos, Zoran Filipi and Dennis Assanis
Automotive Research Center, The University of Michigan

ABSTRACT

The development and use of a simulation of an Integrated Starter Alternator (ISA) for a High Mobility Multi-purpose Wheeled Vehicle (HMMWV) is presented here. While the primary purpose of an ISA is to provide electric power for additional accessories, it can also be utilized for mild hybridization of the powertrain. In order to explore ISA's potential for improving HMMWV's fuel economy, an ISA model capable of both producing and absorbing mechanical power has been developed in Simulink. Based on the driver's power request and the State of Charge of the battery (SOC), the power management algorithm determines whether the ISA should contribute power to, or absorb power from the crankshaft. The system is also capable of capturing some of the braking energy and using it to charge the battery. The ISA model and the power management algorithm have been integrated in the Vehicle-Engine SIMulation (VESIM), a SIMULINK-based vehicle model previously developed at the University of Michigan. Simulation study shows that the ISA powertrain configuration can improve fuel economy over a combined city-highway driving cycle by 4.3% compared to the conventional configuration. Of this gain, 48% is attributed to savings associated with shutting down-restarting the engine, 35% is due to elimination of the engine's inefficient operating points, and 17% is due to brake regeneration.

INTRODUCTION

Medium and heavy trucks powered by Compression Ignition Direct Injection (CIDI) engines constitute a large market segment of the commercial transportation sector, and are also widely used for military tactical operations. In addition to the high thermal efficiency of the CIDI engine, hybridization of conventional powertrain systems has been shown to offer opportunities for achieving even greater fuel economy [1], [2]. This capability is mainly attributed to: a) the potential for downsizing the engine; b) the potential of recovering energy during braking and thus recharging the energy storage unit, (e.g., battery, Ultracapacitor); and c) the ability to minimize the engine's operation in inefficient Brake Specific Fuel Consumption (BSFC) regimes.

The goal of this study is to examine the potential of improving fuel economy in a HMMWV by engaging an ISA for assisting propulsion in a parallel hybrid configuration. This mild hybridization of the powertrain is expected to allow elimination of excessive near-idle engine operation by controlling the ISA torque through a power management algorithm. In addition, shutting-down the engine when the vehicle is at rest is expected to contribute further in avoiding the high BSFC regimes of the engine, shown in red in Figure 1. Clearly, in order to derive benefits from a mild hybrid powertrain incorporating an ISA, the power management algorithm becomes a major concern. This is because the algorithm makes decisions regarding the power split between the thermal and electrical paths, taking into account the current State of Charge (SOC) of the energy storage unit. The objective is to minimize fuel consumption while the driving schedule on demand is satisfied.

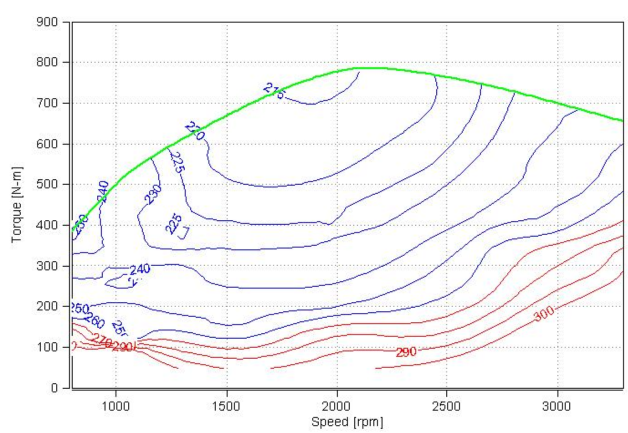

Figure 1: Brake specific fuel consumption (BSFC) map of the international V8 CIDI engine

A number of algorithms have been proposed in the literature based on a priori knowledge of the driving schedule [3-6]. These methods, though not suitable for real-time applications, offer a useful way of evaluating the efficiency of real-time algorithms. Steinmaurer and Del Re [7] focus on a mild hybrid system with ISA, and address engine downsizing and transmission gearing before proposing an optimization-based methodology for generating the ISA control law. The optimization is performed on a set of discrete operating points that are most representative of a given driving schedule. The impact of using light- weight materials, reducing vehicle auxiliary losses and utilizing an efficient operating strategy is discussed in [8]. Other approaches propose real-time power management strategies reliant on an instantaneous optimization of a cost function [9-13]. The cost function consists of the sum of the fuel consumption and the equivalent fuel consumption related to the SOC. This equivalent fuel consumption is generally evaluated under the assumption that every variation in the SOC will be compensated in the future by the engine running at the current operating point.

In the present article, a real-time decision-making algorithm for power management of an ISA mild hybrid is optimized without a priori knowledge of the driving schedule on demand. The development of a feed-forward simulation of an ISA powertrain and its integration in a comprehensive vehicle simulation environment is a prerequisite for optimizing the power management algorithm. The platform used here is the Vehicle-Engine SIMulation (VESIM), a SIMULINK-based vehicle model previously developed in the Automotive Research Center at the University of Michigan [14, 3]. In order to minimize the simulation's computational cost, the ISA model that is developed in this study incorporates a reduced amount of physics, with pre-calculated tables providing torque as a function of speed and efficiency data in terms of torque and speed. The model is capable of capturing interactions in the system and simulating relevant modes of operation, e.g. the ISA running as a motor or generator, power split between the engine and ISA, or capturing of the braking energy by transferring the torque from the wheels upstream to the ISA. The implementation of the proposed algorithm within the power management module and simulation of vehicle operation over a driving schedule allows quantitative assessment of the cumulative fuel economy gains and provides insight into dominant mechanisms responsible for benefits.

This paper is organized as follows. First, the principle of mild hybridization incorporating an ISA system in a parallel configuration is reviewed. Subsequently, the development of the ISA model and its integration into VESIM is described, and the optimum decision-making process established for the power management algorithm is explained. Finally, the integrated simulation environment is used to assess the benefits of mild hybridization of the HMMWV powertrain incorporating and ISA and utilizing an optimized power management algorithm.

PRINCIPLE OF ISA MILD HYBRIDIZATION

Vehicle speed is controlled by the driver through either the accelerator pedal or the brake pedal. Depending on the driving mode, either a positive or a negative torque is requested from the engine; however, in case of braking, if the negative torque provided by the engine is insufficient, friction torque in the wheels provides an additional braking torque which results in energy loss. The engine speed is determined by the transmission and the gear ratio between the engine crankshaft and the wheel. Consequently, the engine torque is the only available variable that can be adjusted in order to operate the engine in efficient BSFC regimes.

For a parallel hybrid configuration, power can be provided for propulsion by both the thermal and electrical paths. The ISA is mechanically coupled to the engine, as depicted in Figure 2.

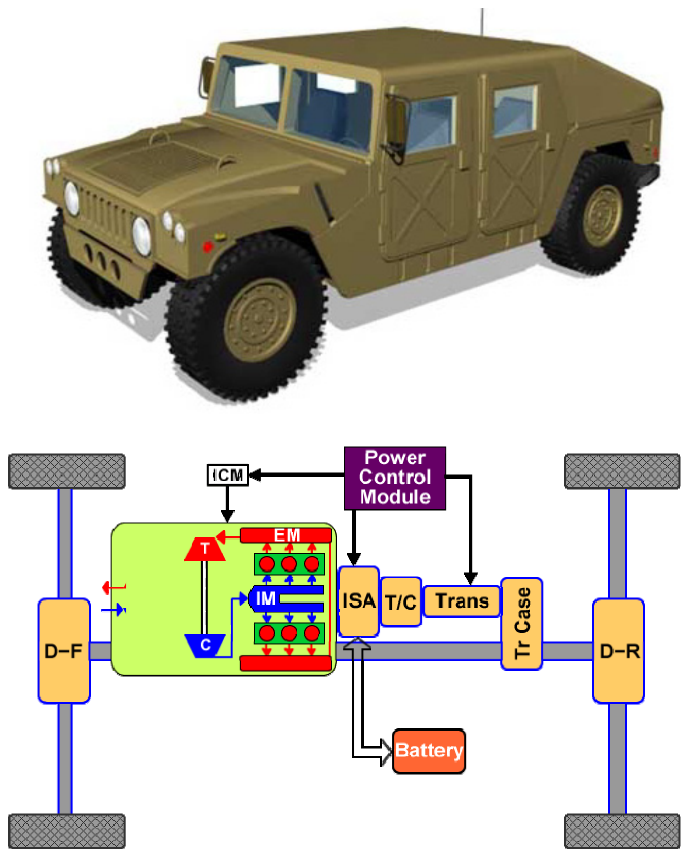

Figure 2: Schematic diagram of the HMMWV powertrain incorporating the ISA
(T-Turbine, C-Compressor, D-F- Front Differential, D-R- Rear Differential, EM- Exhaust Manifold, IM- Intake Manifold, ISA-Integrated Starter Alternator, T/C- Torque Coupler, Trans-Transmission)

Hence, the ISA speed is determined by the engine speed by means of a constant ratio. As a consequence, the additional power available by the ISA can only be regulated by adjusting the ISA torque. The latter can be either positive or negative contingent upon the mode in which the ISA is operating, as designated by the power management algorithm. In the motor mode, the ISA contributes power to the driveline by drawing electrical energy from the battery. In the generator mode, the ISA absorbs power from the driveline and charges the battery.

In cruising, the power requested from the powertrain by the driver is expressed by a positive amount of torque, T_{DRIVER}, given a fixed engine speed:

$$T_{DRIVER} = T_{ENGINE} + T_{ISA} \qquad (1)$$

The power management algorithm comes to a decision regarding the ISA torque, T_{ISA}, based on the current SOC, in order to utilize the most proper engine operating point as far as fuel consumption is concerned.

Conversely, when braking is demanded by the driver, the power is expressed by a negative torque T_{DRIVER}:

$$T_{DRIVER} = T_{ENGINE} + T_{ISA} + T_{BRAKE} \qquad (2)$$

A fraction of this torque is absorbed by the engine, T_{ENGINE}, whereas the ISA absorbs the maximum absolute amount within the constraints imposed by the battery and the ISA. If a residual amount remains, this must be handled by the friction brakes, T_{BRAKE}. Consequently, the ISA can recover the energy that otherwise would be lost by means of friction brakes so as to charge the battery.

HYBRIDIZATION OF HMMWV WITH ISA AND INTEGRATION WITH VESIM

For mild hybridization, the HMMWV powertrain is modified to incorporate an ISA and a battery as an energy storage unit. The ISA is located before the torque converter and it is mechanically coupled with the engine. Accordingly, suitable models for the ISA and battery are developed in SIMULINK and integrated with the rest of the VESIM modules which include the driver, engine, drivetrain, and vehicle dynamics models. Finally, the power management algorithm module is encompassed with the entire model.

ISA MODEL

The ISA is modeled as a 10kW permanent magnet DC electric machine. The efficiency of ISA is a function of torque, T_{ISA}, and speed, ω_{ISA}, and is provided by means of pre-calculated tables given in ADVISOR, a vehicle simulation tool developed by the National Laboratory for Renewable Energy, library [15]:

$$\eta = f(T_{ISA}, \omega_{ISA}) \qquad (3)$$

On condition that ISA operates in the motor mode, the torque is computed by pre-calculated tables [15] as a function of the instantaneous speed, $T(\omega_{ISA})$, and made available subject to the constraints imposed by the battery and the driver's toque request, T_{DRIVER}. The battery constraints are the maximum discharging and charging power limits with respect to SOC [16], max $\{T_{BAT\ DISCH}(SOC)\}$ and max $\{T_{BAT\ CH}(SOC)\}$ respectively, as depicted in Figure 3 and Figure 4. The dynamics of the ISA are approximated by means of a first-order lag with a time constant, τ_{ISA}, equal to 0.05 sec. While the ISA operates on the motor mode, the ISA torque is equal to:

$$T_{ISA} = \min\{T(\omega_{ISA}), \max\{T_{BAT\ DICH}(soc)\}, T_{DRIVER})\} \times \frac{1}{\tau_{ISA} \cdot s + 1} \qquad (4)$$

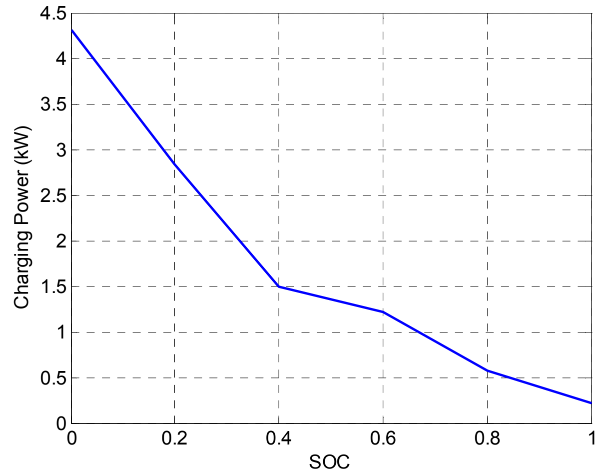

Figure 3: Charging power limit for one module of the battery (Data from ADVISOR)

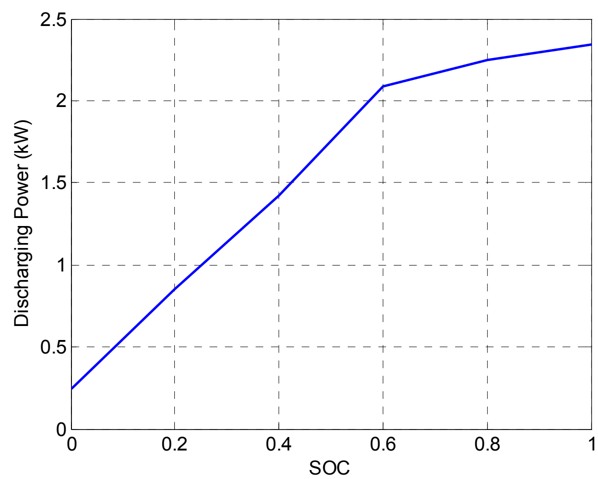

Figure 4: Discharging power limit for one module of the battery (Data from ADVISOR)

Alternatively, in the generator mode, the ISA torque is provided by Equation 5. Note that in this mode the ISA torque is negative.

$$T_{ISA} = \max\{T(\omega_{ISA}), \max\{T_{BAT\ CH}(soc)\}, T_{DRIVER})\} \times \frac{1}{\tau_{ISA} \cdot s + 1} \tag{5}$$

The net power that the ISA absorbs from or delivers to the battery is determined by computing the current, i_{term}, at the battery terminal:

$$i_{term} = \begin{cases} \dfrac{\omega_{ISA} \cdot T_{ISA}}{\eta \cdot e_{term}} & \text{if } T_{ISA} > 0 \\[2ex] \dfrac{\omega_{ISA} \cdot T_{ISA} \cdot \eta}{e_{term}} & \text{if } T_{ISA} < 0 \end{cases} \tag{6}$$

Where, e_{term} is the voltage at the battery terminal, and η is the ISA efficiency.

BATTERY MODEL

A 12 amp-hour battery advanced Valve-Regulated Lead-Acid (VRLA) is used as an energy storage unit. The battery model [17] is two RC circuits connected in series as depicted in Figure 5. The internal resistance, R_{int}, and the open circuit voltage, V_{oc}, are functions of the SOC. The terminal resistance, R_i, as well as the polarization capacitance, C_p, and the incipient capacitance, C_i, are assumed to be constant.

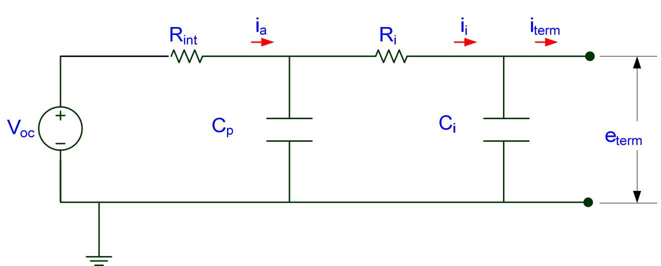

Figure 5: Battery model

The battery has three-order dynamics with the voltages across the capacitors and the SOS being the three states.

VESIM MODEL

VESIM is a high fidelity model developed at the University of Michigan [14] for feed-forward simulations. It has been validated against transient data measured on the proving ground. The Simulink system framework allows easy integration of the vehicle system and addition or substitution of modules depending on the goals of a specific study. The ISA and the power management algorithm are integrated as depicted in Figure 6. Note that the battery model has been incorporated within the ISA module and thus is not illustrated separately. The modified VESIM simulation incorporating the ISA and the power management algorithm is briefly described in the following subsections.

<u>Driver module</u>

The driver module integrates an Intelligent Speed Controller (IVS). The vehicle speed is being delivered into the driver module from the driving schedule on demand and compared with the actual speed which is fed by the vehicle dynamics module. The controller accounts for the discrepancy between the two signals by conveying the accelerating or braking command into the power management algorithm module.

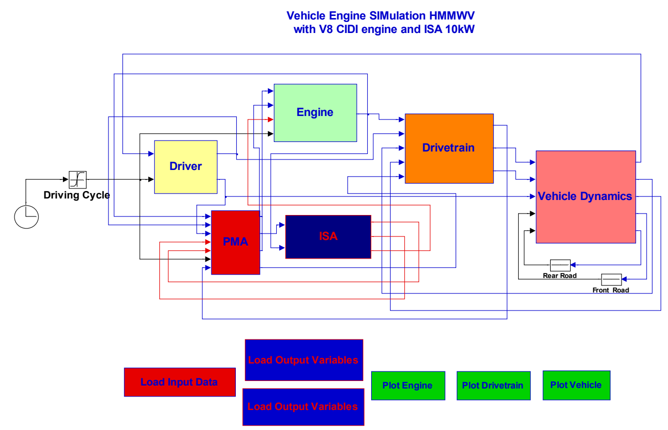

Figure 6: Vehicle Engine SIMulation (VESIM) model integrated with ISA

<u>Engine module</u>

The engine employed for the HMMWV is the International V8 CIDI engine described in Table 1. With the intention of supporting computationally-intensive simulations over long driving schedules on demand, the engine model is based on a torque look-up table rather than a high-fidelity thermodynamic simulation described in [14].

Table 1: International V8 CIDI engine

Variable	Description
Displacement	6.0 L
Aspiration	Variable Geometry Turbine
Fuel Injection	Hydraulic-Electronic Unit-Injectors (HEUI)
Rated Power	246 kW at 3300 RPM
Peak Torque	759 N-m at 2000 RPM

The table provides the engine torque in terms of instantaneous engine speed and mass of fuel injected per cylinder/cycle and it is obtained experimentally in the University of Michigan W. E. Automotive Laboratory. The complete engine system model comprises of the engine torque look-up table, the fuel injection controller and the engine dynamics module, as depicted in Figure 7. The engine speed, ω_{ENGINE}, is computed through the engine dynamics module by applying the Newton's second law:

$$I_{ENGINE} \cdot \dot{\omega}_{ENGINE} = T_{ENGINE} + T_{ISA} - T_{LOAD} \qquad (7)$$

where I_{ENGINE} is the engine inertia and T_{LOAD} is the load torque delivered from the driveline. The ISA torque is propagated through the ISA module.

The fuel injection controller yields the signal for the mass of fuel injected per cycle by means of current engine operating conditions and driver demand fraction as designated by the power management algorithm. This fraction varies between 0 and 1, contingent upon the decision-making process regarding the power split between the engine and the ISA based on the current SOC of the energy battery.

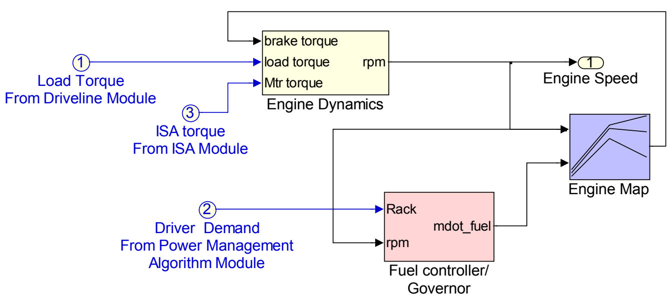

Figure 7: Engine module

Special functions include corrections for insufficient boost pressure, cold start, high altitude, and the governing function. The correction of the amount of fuel based on the boost pressure or density in the intake manifold is especially important during full load acceleration, when turbo lag may cause the engine to operate with much lower boost pressures than normally experienced under corresponding steady-state conditions [18]. The controller has been tested at various steady-state points before it is used for in-vehicle studies. Comparison against experimentally-obtained engine test data confirmed its ability to respond correctly to changes in system operating conditions.

Drivetrain module

The driveline consists of the torque converter, transmission, propshafts, differential, and the drive shafts. It is the intermediate connection between the ISA and the vehicle dynamics, as depicted in Figure 1. The state equations are generated and compiled in a SIMULINK C-MEX function. The shift logic is also coded in another C-MEX file. The two C-MEX functions are combined to form the VESIM driveline module receiving as inputs the engine speed, the wheel rotational speed and the friction brake command from the power management algorithm. The driveline model [20], excluding the shift logic, employs the bond graph modeling language [21 and 22] and has been implemented in the 20SIM system-modeling environment [23].

The torque converter is the fluid clutch by which the ISA is coupled to the transmission. The typical three-element converter consists of an impeller, stator (reactor), and turbine (runner). The impeller is connected rigidly to the ISA output shaft, and the turbine to the transmission input shaft. The stator is connected to the torque converter housing via a one-way clutch. The presence and arrangement of the stator cause the torque converter to act as a torque multiplication device when operating at low speed ratios, and as an approximately direct-drive fluid coupling at higher speed ratios.

Vehicle dynamics module

The vehicle subsystem includes the wheel/tires, axles, suspensions and body of the vehicle. A number of different approaches can be employed to model vehicle dynamics depending on the overall simulation objectives. A single Degree of Freedom (DOF), point mass model provide sufficient fidelity for fuel economy studies. The model [24] assumes that the vehicle mass is lumped at the center of gravity, as depicted in Figure 8. The model is composed of two components that describe the dynamic behavior of the vehicle in the longitudinal and heave directions. The components are coupled through the road/tire interaction.

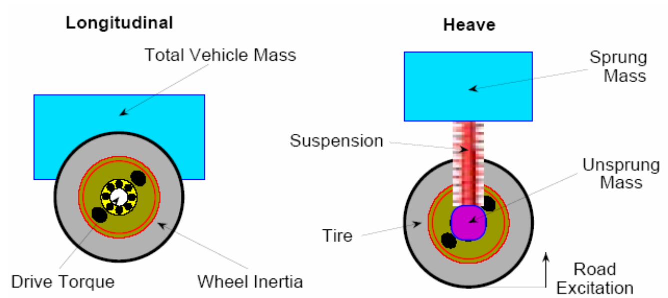

Figure 8: Schematic of vehicle dynamics

POWER MANAGEMENT ALGORITHM

The power management algorithm in the mild hybrid powertrain configuration with ISA is charged with the decision-making process concerning with the power split between the engine and the ISA. The algorithm is applied to the acceleration and cruising conditions. Braking event is controlled by a rule that reverses the

ISA when the driver applies the brake and attempts to provide the required braking torque by the ISA.

The theory of events of strategy [25] is described as a mathematical theory of decision-making by participants in either a competitive or cooperative environment. It is widely applicable in problems where each participant can bring some influence to bear upon the outcome (payoff) of a certain event; no single participant by himself/herself nor chance alone can completely determine the outcome. The theory is then concerned with the problem of choosing an optimal course of action which takes into account the possible actions of the participants and the chance events. An event of strategy is described by its set of rules. These rules specify clearly what each participant is allowed or required to do under all possible circumstances.

An optimum decision-making process applied among the available operating conditions of the engine and the ISA at each instant of time (event) is employed for the power management algorithm. The participants in this process are the engine and the ISA. Each participant has a number of different strategies (amount of power) representing its available operating conditions. Suppose that the engine has m strategies and the ISA has n strategies; then the decision-making process is determined by the $m \times n$ matrix $A = (a_{ij})$.

$$A = \begin{pmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{m1} & \cdots & a_{mn} \end{pmatrix} \tag{8}$$

Where a_{ij} is the engine's payoff (BSFC value) if the engine uses its ith strategy and the ISA uses its jth strategy.

The engine employs only one strategy corresponding to driver's power request whereas the ISA exploits five different strategies: motor 100%; motor 50%; generator 100%; generator 50%; and the shut off mode. The 50% motor or 50% generator implies half of the maximum available amount of power, whereas the motor and generator 100 % utilizes the entire available maximum amount. The proposed ISA strategies are designated by the upper charging and discharging power limits for the given SOC of the battery as imposed by the ISA limitations. Subsequently, as SOC is varied the proposed ISA strategies are varied respectively and thus two dynamically varying power curves (motor and generator) are developed around engine's proposed power composing the limits of the current available engine operating points. Ideally, the entire ISA available operating range should be considered in continuous manner; however, given the small size of the ISA compared with the engine, the five discrete ISA operating conditions are sufficient to capture the feasible domain and enable the current best engine operating point. More intermediate ISA power curves between the maximum of the motor and generator did not affect seriously the fuel economy outcome.

The payoff elements of matrix A are computed for each event by subtracting from the engine's strategy power (corresponding to driver's power request) the amount of power proposed by each ISA strategy, which is then matched to the BSFC map. The frequency of an event happening is determined by the rate of driver's power request.

$$a_{ij} = BSFC(\overset{i<m}{P}_{\text{ENGINE}} - \overset{j<n}{P}_{ISA}) \tag{9}$$

Therefore, the decision-making process is concerned with deriving the combination of each participant's strategy in real-time providing the optimum outcome, namely, the least BSFC value.

$$(i, j) = \min_{\substack{i<m \\ j<n}} a_{ij} \tag{10}$$

Subsequently, the outcome of the decision-making process, *(i,j)*, determines the most suitable ISA mode and the amount of power respectively, as far as the fuel consumption is concerned, while the driver's schedule on demand is satisfied. Switch logic maintains the SOC in a range of 35 -85% as indicated by the battery's lifetime guidelines. When SOC reaches any of these two limits the motor and generator mode strategies propose zero power respectively, with the intention of allowing the battery to operate on the suitable SOC range.

SIMULATION RESULTS

Vehicle simulation is performed for each individual powertrain configuration, e.g., conventional and with ISA. Given vehicle's type and relatively large weight, a combined driving schedule is devised using elements of the Federal Urban (1090 seconds) and Highway (310 seconds) driving schedules. This is more representative of missions encountered by military multi-purpose trucks than using standard cycles originally developed for passenger cars and light trucks. Both powertrain configurations demonstrate the ability to track the demanded driving schedule accurately, as depicted in Figure 9.

The driver' power request, as well as the engine and ISA power delivered to the driveline with respect to time is illustrated in Figure 10. The ISA alternatively operates in either motor or generator mode as designated by the power management algorithm. It is noted that the 50% generator strategy is never selected over the entire driving schedule. In other words, when a decision is made to move the engine operating point into the more efficient region it was always beneficial to use the full potential of the integrated alternator.

The interactions in the system in the conventional and hybridized propulsion system are compared in Figure 11. The engine speed trace, depicted in Figure 11a, illustrates the frequency of engine shut-downs. Avoiding engine idling, when the vehicle is at rest, enables direct fuel savings. The comparison of engine torque histories, depicted in Figure 11b, demonstrates reductions of engine torque achieved by replacing part of driver demand with ISA output. Occasionally, the engine torque in the ISA-equipped powertrain is above the corresponding value in the conventional powertrain and thus indicates battery charging events. The transient nature of ISA operation is illustrated in Figure 11c. The different charging rates that are noticed correspond to braking and depend on the deceleration profiles required by the driver. The SOC profile, depicted in Figure 11d demonstrates that the system maintains near-constant SOC over the driving schedule. This is not required by the power management algorithm; however, it is a result of a rather fortunate combination of charging/discharging events. Any change in initial conditions, or in the driving schedule, could lead to a different outcome.

The zoom-in into a segment of the driving schedule, shown in Figure 12, provides a more detailed insight into energy recovery during braking. The differences in charging rates and the slope of the SOC variation can be linked to different deceleration rates and initial levels of kinetic energy. Figure 13 and Figure 14 illustrate engine operating points on the torque-speed plot of the conventional and ISA powertrain, respectively. Comparison of the two graphs provides qualitative insight into the effectiveness of the power management algorithm to move engine operating points out of the inefficient zones. The first observation is an almost complete absence of engine operating points below a certain power level. Specifically, the algorithm is avoiding low efficiency points by engaging the ISA in the most suitable mode. The changes close to the upper bound are less obvious, but some of the unusual shapes can be tied to the somewhat irregular, nevertheless contours.

Figure 15 illustrates the cumulative fuel consumption and the battery SOC for both powertrain configurations. Since the initial and final levels of SOC are equal, the fuel economy savings evident in the ISA case are illustrated realistically. Overall, the hybrid powertrain demonstrates a 4.3 % fuel economy improvement as summarized in Table 2. In addition, the simulation was executed three times, each time with a different power management function disabled. This allows for a classification of fuel economy improvement. Table 3 summarizes the results, i.e. quantitative contribution of shutting down-restarting the engine, regeneration and elimination of inefficient engine operating points. Shutting down-restarting the engine is the main factor in the fuel economy improvement, while regeneration contributes the least. The small contribution of regeneration is in contrast to findings on a parallel hybrid powertrain featuring a post-transmission motor location and a much larger motor/generator [18], and subsequently, it was expected. In the mild hybrid powertrain configuration, the ISA is much smaller; in addition, it is located far upstream from the wheels and some of the potential benefits are lost due to mechanical inefficiencies in the complete driveline. In contrast, the gains obtained through manipulating engine speed/load trajectories are more tangible due to direct interactions between the ISA and the engine. This type of information can provide a very useful guidance for design decisions and refinements of the component characteristics.

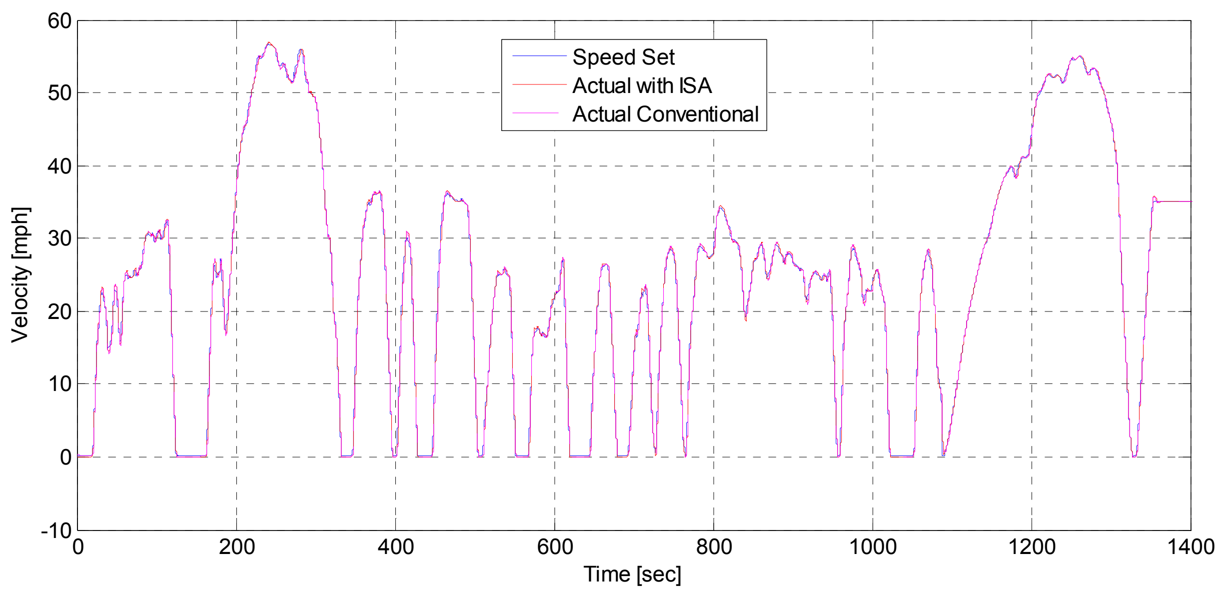

Figure 9: The combined driving schedule for the HMMWV: comparison of prescribed and simulated speed profiles.

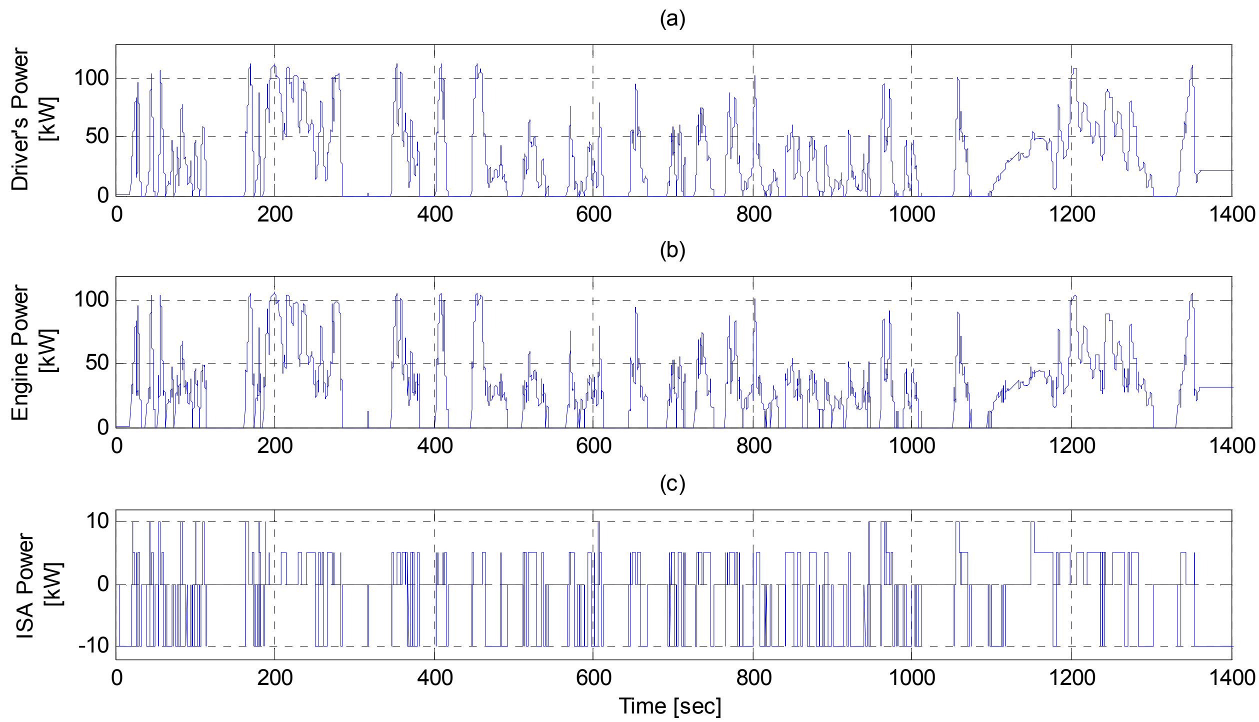

Figure 10: Driver's power request, engine and ISA power delivered to driveline

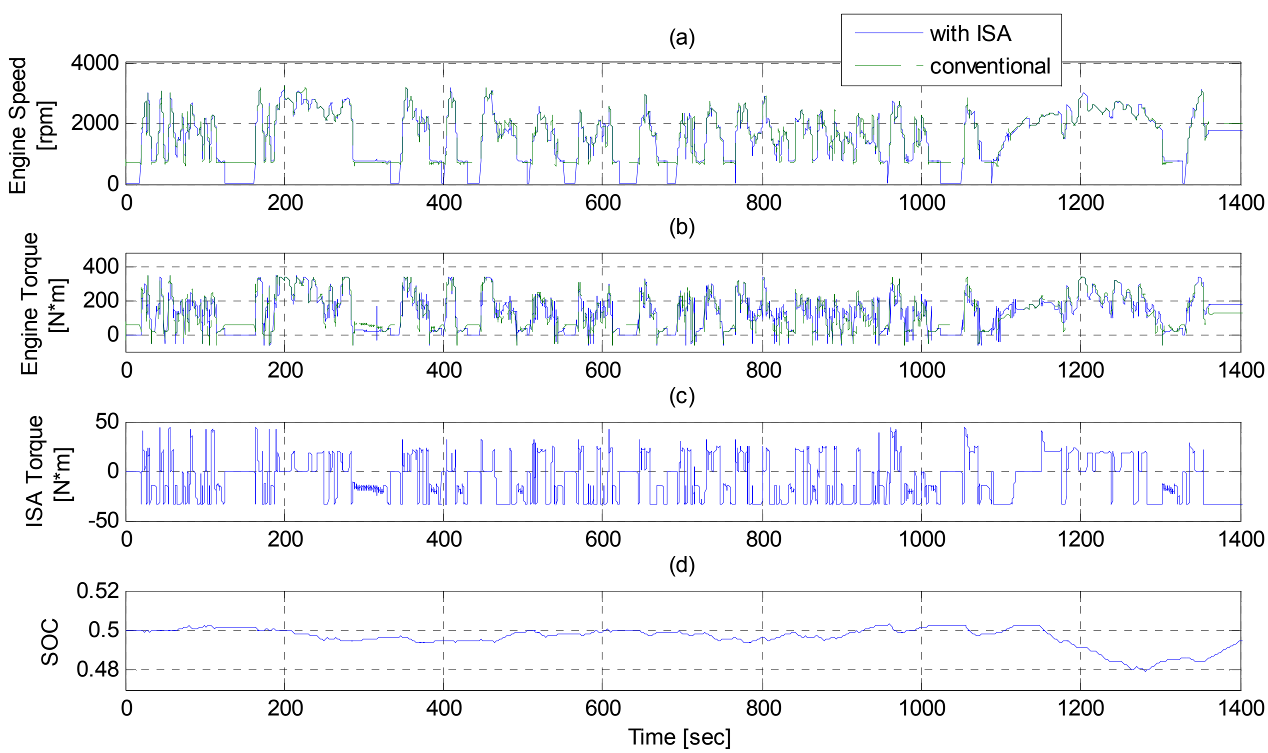

Figure 11: Engine Performance, ISA torque and SOC

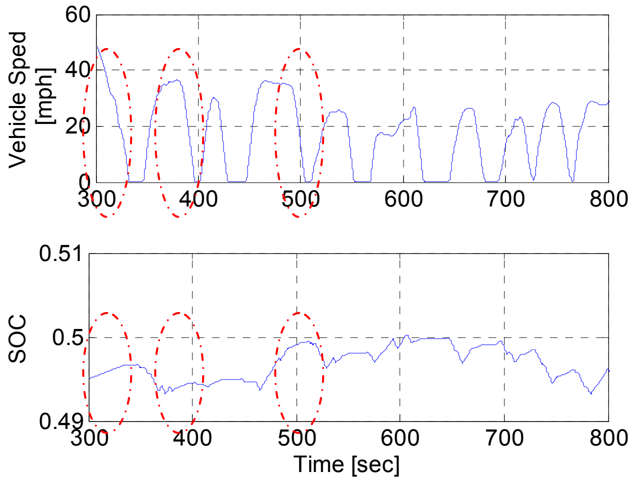

Figure 12: Brake regeneration of the hybridized powertrain for a part of schedule

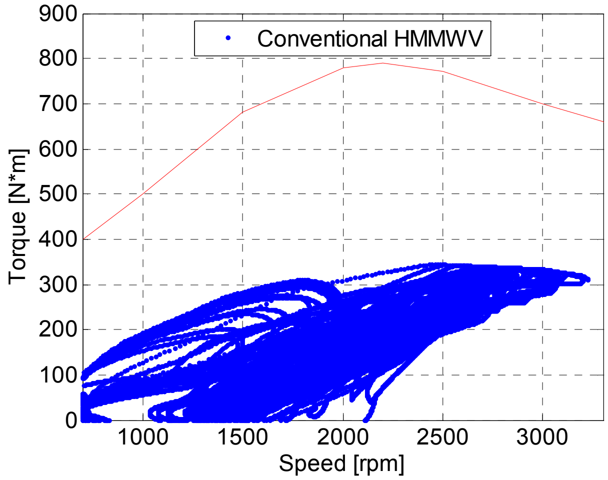

Figure 13: Engine operating points of the conventional powertrain

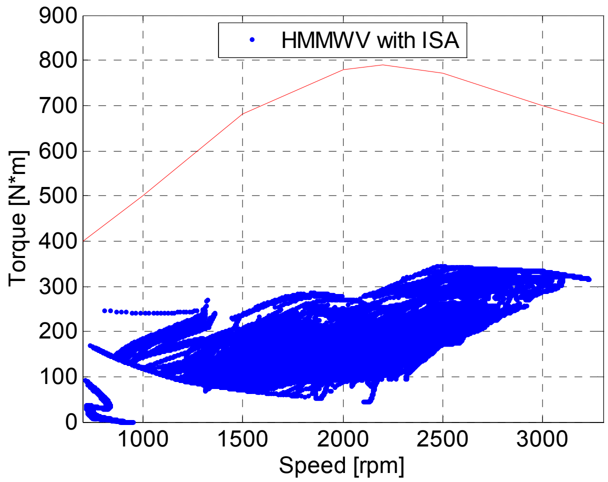

Figure 14: Engine operating point of the powertrain with ISA

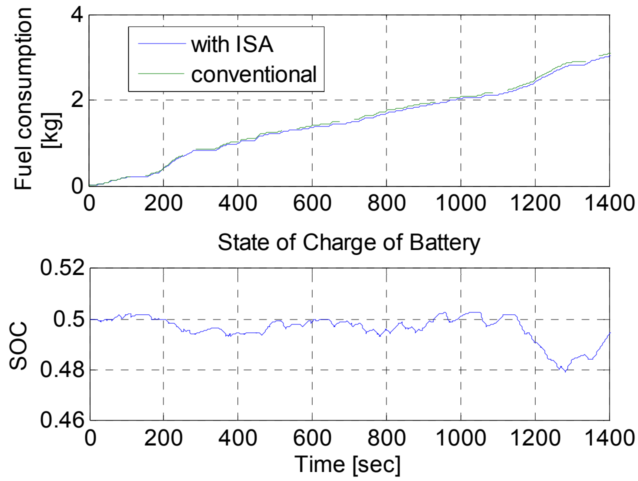

Figure 15: Fuel consumption over the schedule on demand and SOC of the battery

Table 2: Fuel consumption resulting from simulation of the first 1400 sec of the driving cycle with 50% initial and final SOC

	Fuel Consumption [kg]	**MPG**	**Improvement in MPG**
Conventional HMMWV	3.143	9.54	-
HMMWV with ISA	3.025	9.95	4.29%

Table 3: Fuel economy improvement classification

Fuel Economy Advancement Attributed to	
Shut off-Restarting	48%
Brake Regeneration	17%
Elimination Inefficient Engine Operating Points	35%

SUMMARY AND CONCLUSIONS

This study explored the potential of improving fuel economy of a medium size 4x4 HMMWV truck through a mild hybridization using an Integrated Starter Alternator (ISA). Both the conventional and the mild hybrid propulsion system were modeled using a combination of physics based models and experimentally derived look-up tables. The integration of the complete vehicle system was performed in SIMULINK. The fidelity of particular models was selected in the light of the ultimate objective of using the optimization algorithms for decision-making regarding power management.

The power management algorithm in the mild hybrid powertrain configuration with ISA employed a decision-making process for the power split between the engine and the electric machine. The main objective in its development was to maximize fuel economy benefits from mild hybridization. In addition, it was shown capable of accommodating dynamic changes of battery charging or discharging limits, and hence ISA power boundaries.

The major conclusions to be drawn from this study based on the results over the combined driving schedule and comparisons of the conventional powertrain and mild hybrid powertrain with ISA configurations are the following:

- The application of 10 kW ISA for mild hybridization in conjunction with the power management algorithm allowed a 4.3% improvement in fuel economy.
- A real-time power management algorithm is critical for realizing the fuel economy benefits in the ISA hybrid-electric system due to the small size of the electric machine and its limited potential for regeneration.
- The classification of the benefits through a systematic simulation study indicates that the engine shutting down is the major contributor, followed by the elimination of inefficient engine operating points. Regeneration contributes the least due to the ISA power limits and location furthest upstream from the wheels.

ACKNOWLEDGMENTS

The authors wish to acknowledge the technical and financial support of the Automotive Research Center (ARC) by the National Automotive Center (NAC), and the U.S. Army Tank-Automotive Research, Development and Engineering Center (TARDEC). The ARC is a U.S. Army Center of Excellence for Automotive Research at the University of Michigan, currently in partnership with the University of Alaska-Fairbanks, Clemson University, University of Iowa, Oakland University, University of Tennessee, and Wayne State University. The authors would also like to thank Mr. Jonathan Hagena and Mr. Alexander Knafl for providing valuable engine experimental data. Dr. Loucas Louca and Dr. Hosam Fathy are thanked for their assistance in modifying the torque converter and vehicle dynamics model in VESIM.

REFERENCES

1. J. Walters, H. Husted and K. Rajashekara, “Comparative Study of Hybrid Powertrain Strategies,” SAE Technical Paper No. 2001-01-2501.
2. C. S. Sloane, B. E. Zemke, et al, “Rationale for Technology Selections in GM’s PNGV Precept Concept Car based on System Analysis,” SAE Technical Paper No. 2000-01-156.
3. C. Lin, Z. Filipi, Y. Wang, L. Louca, H. Peng, D. Assanis, and J. Stein, “Integrated, Feed-forward Hybrid Electric Vehicle Simulation in SIMULINK and its Use for Power Management Studies,” SAE Technical Paper No. 2001-01-1334.
4. S. Delprat, T.Guerra, G. Paganelli, J. Lauber, and M. Delhom, “Control Strategy Optimization for an Hybrid Parallel Powertrain,” Proc. 2001 American Control Conference, Arlington, TX, 2001.
5. Z. Han, Z. Yuan, T. Guangyu and C. Quanshi, “Optimal Energy Management Strategy for Hybrid Electric Vehicles,” SAE Technical Paper No. 2004-01-0576.
6. A. Brahma, Y. Guezennez, and G. Rizzoni, “Optimal Energy Management in Series Hybrid Electric Vehicle,” Proc. American Control Conference 2000, Chicago, IL, 2000.
7. G. Steinmaurer, L. del Re, “Optimal Energy Management for Mild Hybrid Operation of Vehicles with an Integrated Starter Generator,” SAE Technical Paper No. 2005-01-0280.
8. A. Jaura, W. Buschhaus and M. Tamor, “Systems Approach in Achieving Higher Fuel Economy in Hybrid Vehicles,” SAE Technical Paper No. 2000-01-1585.
9. A. Sciarreta, M. Back, and L. Guzzela, “Optimal Control of Parallel Hybrid Electric Vehicles,” IEEE Transactions on Control Systems Technology, vol. 12, no. 3, May 2004.
10. G. Paganelli, S. Delprat, T. Guerra, J. Rimaux, and J. Santin, ”Equivalent Consumption Minimization Strategy for Parallel Hybrid Powertrains,” Proc. Fall VTC-01 Conference Sponsored by VTS (Vehicular Technology Society) and IEEE, Atlantic City, NJ, 2001.
11. V. Johnson, K Wipke, and D Rausen, “HEV Control Strategy for Real-Time Optimization of Fuel Economy and Emissions,” SAE Technical Paper No. 2000-01-1543.
12. G. Paganelli, A. Brahma, G. Rizzoni, and Y. Guezennec, “Control Development for a Hybrid-Electric Sport-Utility Vehicle: Strategy, Implementation and Field Test Results,” Proc. 2001 American Control Conference, Arlington, TX, 2001.
13. G. Paganelli, T. Guerra, S. Delprat, J. Santin, E. Combes, and M. Delhom, “Simulation and Assessment of Power Control Strategies for a Parallel Hybrid Car,” J. Automobile Eng., vol. 214, pp.705-718, 2000.
14. D. Assanis, Z. Filipi, S. Gravante, D. Grohnke, X. Gui, L. Louca, G. Rideout, J. Stein, Y. Wang, “Validation and Use of Simulink Integrated, High Fidelity, Engine-In-Vehicle Simulation of the International Class VI Truck,” SAE Technical Paper No. 2000-01-0288.

15. S. Burch, M. Cuddy, "Advisor 2.1 Documentation," National Renewable Energy Laboratory, March 1999.
16. H. Wiegman, A. Vandenput, "Battery State Control Techniques for Charge Sustaining Applications," SAE Technical Paper No. 981129, 1998.
17. B. Powel, T. Pilutti, "A Range Extender Hybrid Electric Vehicle Dynamic Model," Proceedings of the 33rd IEEE Conference on Decision and Control, Lake Buena Vista, FL, December 1994.
18. Lin, C-C., Filipi, Z., Loucas, L., Peng, H., Assanis, D., Stein, J.,"Modeling and Control for a Medium-Duty Hybrid Electric Truck," International Journal of Heavy Vehicle Systems, Vol. 11, Nos. 3/4, 2004, pp. 349-370
19. Wu, B., Lin, C.-C., Filipi, Z., Peng H., Assanis, D., "Optimal Power Management for a Hydraulic Hybrid Delivery Truck," Journal of Vehicle System Dynamics, Vol. 42, Nos. 1-2, 2004, pp. 23-40
20. L. Louca, J. Stein, and D. Rideout, "Generating Proper Integrated Dynamic Models for Vehicle Mobility Using a Bond Graph Formulation," Society for Computer Simulation, Phoenix, AZ, January 2001.
21. D. Karnopp, D. Margiolis, R. Ronsenberg, System Dynamics: A Unified Approach. Wiley-Interscience, New York, NY, 1990.
22. R. Rosenberg, D. Karnopp, Introduction to Physical System Dynamics. McGraw-Hill, New York, NY, 1983.
23. 20SIM, 20SIM Pro User's Manual. The University of Twent-Controllab Products B.V. Enschede, The Netherlands, 1999.
24. L. Louca, J. Stein, G. Hulbert, "A Physical-Based Model Reduction Metric with an Application to Vehicle Dynamics," The 4th IFAC Nonlinear Control Systems Design Symposium (NOLCOS 98), Enschede. The Netherlands, 1998.
25. M. Dresher, The Mathematics of Games of Strategy: Theory and Applications, Dover Publications, Inc., New York, 1980.

DEFINITIONS, ACRONYMS, ABBREVIATIONS

ISA: Integrated Starter Alternator
HMMWV: High Mobility Multi-purpose Wheeled Vehicle
SOC: State of Charge
VESIM: Vehicle Engine SIMulation
CIDI: Compression Ignition Direct Injection
SI: Spark Ignition
PNGV: Partnership for a New Generation of Vehicles
BSFC: Brake Specific Fuel Consumption
CVT: Continuously Variable Transmission
BAT DICH: Battery Discharging
BAT CH: Battery Charging
VRLA: Valve-Regulated Lead-Acid
IVS: Intelligent Speed Controller
DOF: Degree of Freedom
MPG: Miles Per Gallon