A Matlab-Based Modeling and Simulation Package for Electric and Hybrid Electric Vehicle Design

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***Abstract*— This paper discusses a simulation and modeling package developed at Texas A&M University, V-Elph 2.01. V-Elph facilitates in-depth studies of electric vehicle (EV) and hybrid EV (HEV) configurations or energy management strategies through visual programming by creating components as hierarchical subsystems that can be used interchangeably as embedded systems. V-Elph is composed of detailed models of four major types of components: electric motors, internal combustion engines, batteries, and support components that can be integrated to model and simulate drive trains having all electric, series hybrid, and parallel hybrid configurations. V-Elph was written in the Matlab/Simulink graphical simulation language and is portable to most computer platforms.**

This paper also discusses the methodology for designing vehicle drive trains using the V-Elph package. An EV, a series HEV, a parallel HEV, and a conventional internal combustion engine (ICE) driven drive train have been designed using the simulation package. Simulation results such as fuel consumption, vehicle emissions, and complexity are compared and discussed for each vehicle.

***Index Terms*—Electric vehicle, hybrid electric vehicle, modeling, simulation.**

I. INTRODUCTION

PRESENTLY, only electric and low-emissions hybrid vehicles can meet the criteria outlined in the California Air Regulatory Board (CARB) regulations which require a progressively increasing percentage of automobiles to be ultralow or zero emissions beginning in the year 1998 [1]. Though purely electric vehicles (EV's) are a promising technology for the long-range goal of energy efficiency and reduced atmospheric pollution, their limited range and lack of supporting infrastructure may hinder their public acceptance [2]. Hybrid vehicles offer the promise of higher energy efficiency and reduced emissions when compared with conventional automobiles, but they can also be designed to overcome the range limitations inherent in a purely electric automobile by utilizing two distinct energy sources for propulsion. With hybrid vehicles, energy is stored as a petroleum fuel and in an electrical storage device, such as a battery pack, and is converted to mechanical energy by an internal combustion engine (ICE) and electric motor, respectively. The electric motor is used to improve energy efficiency and vehicle emissions while the ICE provides extended range capability. Though many different arrangements of power sources and converters are possible in a hybrid power plant, the two generally accepted classifications are series and parallel [3].

Computer modeling and simulation can be used to reduce the expense and length of the design cycle of hybrid vehicles by testing configurations and energy management strategies before prototype construction begins. Interest in hybrid vehicle simulation grew in the 1970's with the development of several prototypes that were used to collect a considerable amount of test data on the performance of hybrid drive trains [4]. Studies were also conducted to analyze hybrid electric vehicle (HEV) concepts [5]–[11]. Several computer programs have since been developed to describe the operation of hybrid electric power trains, including: simple EV simulation (SIMPLEV) from the DOE's Idaho National Laboratory [12], MARVEL from Argonne National Laboratory [13], CarSim from AeroVironment Inc., JANUS from Durham University [14], ADVISOR from the DOE's National Renewable Energy Laboratory [15], Vehicle Mission Simulator [16], and others [17], [18]. A previous simulation model (ELPH) developed at Texas A&M University was used to study the viability of an electrically peaking control scheme and to determine the applicability of computer modeling to hybrid vehicle design [19], but was essentially limited to a single vehicle architecture. Other work conducted by the hybrid vehicle design team at Texas A&M University is reported in papers by Ehsani *et al.* [20]–[24].

V-Elph [25], [26] is a system-level modeling, simulation, and analysis package developed at Texas A&M University using Matlab/Simulink [27] to study issues related to EV and HEV design such as energy efficiency, fuel economy, and vehicle emissions. V-Elph facilitates in-depth studies of power plant configurations, component sizing, energy management strategies, and the optimization of important component parameters for several types of hybrid or electric configuration or energy management strategy. It uses visual programming techniques, allowing the user to quickly change architectures, parameters, and to view output data graphically. It also includes detailed models that were developed at Texas A&M University of electric motors, internal combustion engines, and batteries.

This paper discusses the methodology for designing system-level vehicles using the V-Elph package. An EV, a series HEV, a parallel EV, and a conventional ICE driven drive train have been designed using the simulation package. The simulation results are compared and discussed for each vehicle.

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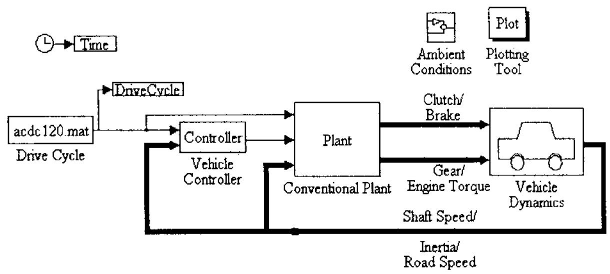


Fig. 1. System-level representation of a general vehicle drive train in V-Elph.

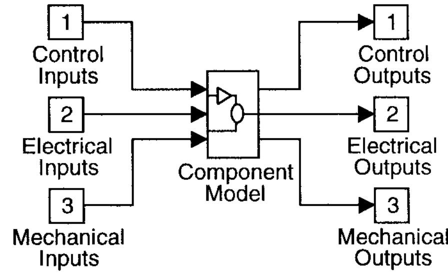


Fig. 2. Component input/output interface.

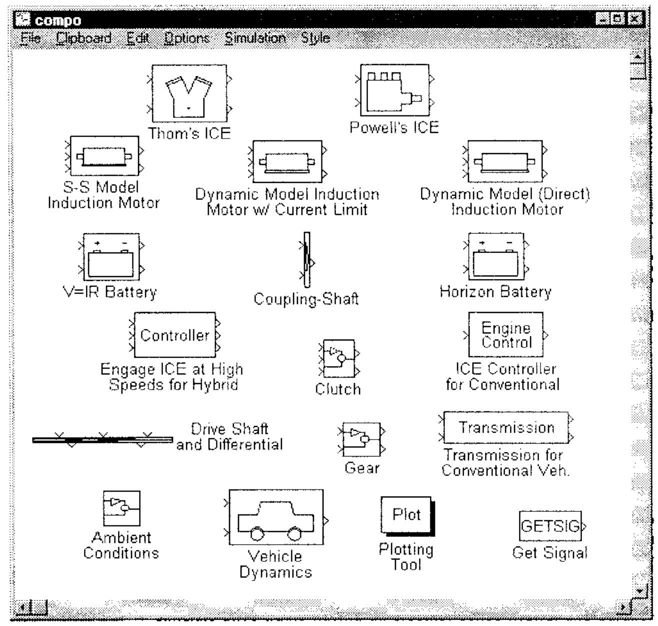


Fig. 3. Library of components.

II. Drive Train Design Methodology

Several levels of depth are available in V-Elph to allow users to take advantage of the features that interest them. At the most basic level, a user can run simulation studies by selecting an EV, series, or parallel hybrid vehicle, or conventional vehicle drive train model provided and display the results using the graphical plotting tools. In addition to being able to change the drive cycle and the conditions under which the vehicle operates, the user can switch components in and out of a vehicle model to try different types of engines, motors, and battery models. The user can also change vehicle characteristics such as size and weight, gear ratios, and the size of the components that make up the drive train.

An intermediate user can create his/her own vehicle configurations using a blank vehicle drive train template as shown in Fig. 1. This drive train was constructed graphically by connecting the main component blocks (drive cycle, controller, power plant, and vehicle dynamics) using the Simulink visual programming methodology through the connection of the appropriate input and output ports. The power plant is blank and is designed using component models selected from a component library. Components can be isolated to run parameter sweeps that create performance maps which assist in component sizing and selection. A controller block is designed with logic statements which create the signals required to control the individual system-level components. A vehicle dynamics block is designed with input parameters such as road angle, mass, and drag coefficient necessary to compute vehicle output dynamic parameters such as engine speed and road speed. The drive cycle block is designed by selecting a drive cycle from those supplied by the package or creating a new drive cycle.

Finally, advanced users can pursue sophisticated design objectives such as the creation of entirely new component models and the optimization of a power plant by creating add-on features that are compatible with the modeling system interface. V-Elph allows the interconnection of many types of electrical or mechanical component utilized in a vehicle drive train, even experimental technologies such as ultracapacitors. Component models can be created from lookup tables, empirical equations, and both steady-state and dynamic equations. Each component model is created using the general model and interface shown in Fig. 2. The component models are stored in a library, called the library of components as shown in Fig. 3. The speed at which the simulation executes is highly dependent on the complexity of the component models used in a vehicle design. Various detailed component models are currently utilized in the V-Elph package. They were developed by members of the ELPH research team at Texas A&M University and designed based on steady-state and dynamic equations.

III. Design of Vehicle Drive Trains

In this section, the design and analysis of an EV drive train, two parallel HEV drive trains with different control strategies, a series HEV drive train, and a conventional ICE-driven vehicle drive train using the V-Elph package are discussed. A description is given of the performance specifications and the control strategy and power plant developed for each vehicle design. A typical mid-sized family sedan was used as the basis for each vehicle. The vehicles' components were sized to provide enough power to maintain a cruising speed of 120 km/h on a level road and an acceleration performance of 0–100 km/h in 16 s for short time intervals. The vehicles were also designed to maintain highway speeds for several hundred seconds. The ICE, motor, battery, and vehicle dynamics models were appropriately customized to meet the specific vehicle performance requirements for each vehicle design.

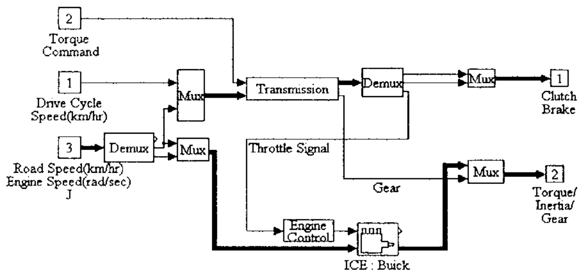


Fig. 4. Power plant representation of conventional vehicle drive train designed using V-Elph.

TABLE I
SPECIFICATIONS OF ICE DRIVE TRAIN

Engine Specifications			
Total Displacement		3.791 liter	
Max Torque		298 Nm at 3200 rpm	
Max Power		125 KW at 4800 rpm	
Vehicle Specifications			
Curb Weight		1580 kg	
Acceleration		0-60 mph in 10 s	
Overall Gear Ratios			
1st	2nd	3rd	4th
8.94	4.804	3.06	2.142

Simulation studies were performed for each vehicle using a simple acceleration and deceleration drive cycle, an FTP-75 urban drive cycle, a federal highway drive cycle, and a commuter drive cycle. Various performance parameters generated during the simulation studies are graphically presented in the paper. A table is included which compares performance parameters such as fuel consumption and emissions for each simulation study.

A. ICE Conventional Drive Train Design

The conventional ICE-driven drive train was designed based on the specifications of a Buick LeSabre (1991 model) [28]. The vehicles four-speed automatic transmission was modeled as a manual transmission with a clutch, retaining the same overall gear ratios. It is a four-door sedan six-passenger vehicle with a desired 0–60 mph in the 10-s range characteristic and a curb weight of 3483 lbs (1580 kgs). The power plant is shown in Fig. 4. Table I shows the engine and vehicle specifications utilized to design the conventional drive train.

B. Parallel Hybrid Electric Drive Train Design

In a typical parallel design, consisting of an ICE and an electric motor in a torque-combining configuration, either the ICE or the electric motor can be considered the primary energy source depending on the vehicle design and energy management strategy. The drive train can also be designed so that the ICE and electric motor are both responsible for propulsion or each is the prime mover at a certain time in the drive cycle. A component's functional role could change within the course of a drive cycle due to battery depletion or other vehicle requirements. Vehicle architecture decisions, control strategies, component selection and sizing, gearing, and other design parameters become considerably more complex in a parallel hybrid due to the sheer number of choices and their effect on a vehicles performance given a particular mission.

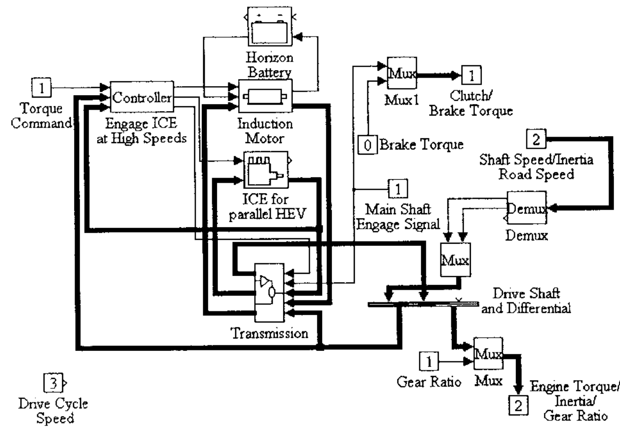


Fig. 5. Parallel HEV drive train configuration.

The vehicle drive train configuration in Fig. 5 was designed in V-Elph for a parallel HEV. It is based on a typical mid-sized family sedan with a gross mass of 1838 Kg that includes the additional batteries used in the hybrid power plant. The drive train includes a controller which manipulates the torque contributions of the electric motor and ICE. The battery provides power for the induction motor. The ICE model was sized to provide enough power to maintain a cruising speed of 120 km/h on a level road and the electric machine was sized to provide acceptable acceleration performance of 0–100 km/h in 16 s for short time intervals.

The ICE model was designed based on Powells engine analysis [29]. The induction machine model [20] performs two functions in the drive train: as a motor it provides torque at the wheels to accelerate the vehicle, and as a generator it recharges the battery during deceleration (regenerative braking) or whenever the torque produced by the power plant exceeds the demand from the driver. Vector control was utilized to extend the constant power region of the motor, making it possible to run the motor over a wide speed range. The motor can provide the requested torque up to the constant power threshold at speeds above the base speed of the motor; operation beyond this point is restricted to avoid exceeding the motor's power rating. The HEV design utilizes the wide speed range of the vector-controlled induction motor to improve the overall system efficiency.

The battery model [23] uses the current load and battery state of charge to determine dc bus voltage. Voltage tends to drop as the state of charge decreases and as the amount of current drawn from the battery increases. At low currents, the battery efficiency is reasonably high regardless of the state of charge.

Two parallel HEV drive trains were designed using different control strategies, referred to as control strategy 1 and control strategy 2. Control strategy 1 operates such that the ICE runs at a constant fuel throttle angle and the electric machine makes up the difference between the torque requested by the driver and the torque produced by the ICE. This scheme aims

TABLE II
COMPONENTS OF PARALLEL HYBRID DRIVE TRAIN

ICE	1.0 liter, 32.5 kW
Motor	Vector controlled, 40 kW
Battery	13, 12-volt, lead acid cells in series, 85 A•h per cell

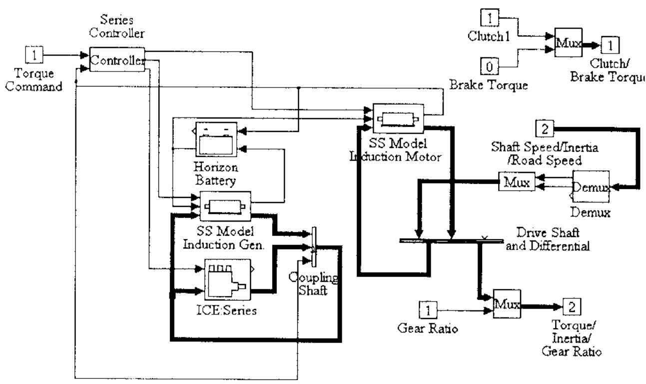


Fig. 6. Drive train for series hybrid vehicle.

TABLE III
COMPONENTS OF SERIES HYBRID DRIVE TRAIN

ICE	1.2 liter, 40 kW
Motor	Vector controlled, 40 kW
Generator	Vector controlled, 40 kW
Battery	13, 12-volt, lead acid cells in series, 85 A•h per cell

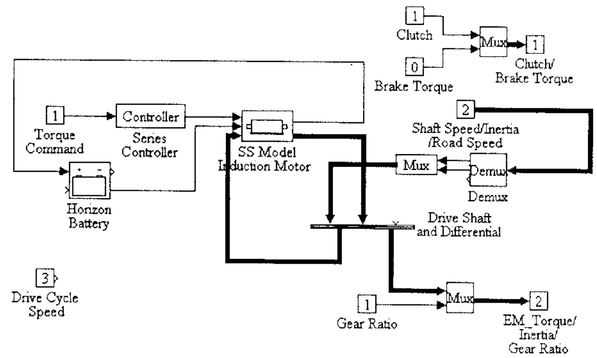


Fig. 7. EV drive train.

to minimize the amount of time that the ICE is in use by maximizing the speed at which the ICE is engaged to the wheels while maintaining the battery state of charge over the drive cycle. Control strategy 2 operates such that the ICE runs over its entire speed range and makes the ICE throttle angle a function of speed to meet the steady-state road load. The general principle behind each strategy is that the electric motor provides power for propulsion during the transients, acceleration to deceleration, and the ICE provides propulsion during cruising.

The sizes of the components for the parallel hybrid drive train are stated in Table II.

C. Series Hybrid Electric Drive Train Design

In a series hybrid EV, only one energy converter provides torque to the wheels while the others are used to recharge an energy accumulator, usually a battery pack. In a typical series hybrid design, an ICE/generator pair charges the batteries and only the motor actually provides propulsion. The series hybrid drive train shown in Fig. 6 includes a controller and power plant and was designed based on Hochgraf's work [30]. A vector-controlled induction motor powered by a dc battery pack of 156 V supplies the power at the drive wheels. In addition, there is an auxiliary power unit (APU) comprising of an ICE driving an induction generator. The APU supplies power to the battery when the demanded current by the induction motor exceeds a threshold value of 75 A. The local controller is responsible for the following tasks:

- demanding a torque (positive or negative) from the induction motor depending on drive cycle requirements;
- for switching on/off the APU.

The torque demanded from the induction motor is positive during acceleration and cruise phases of the drive cycle (motoring mode) and is negative during the deceleration phase of the drive cycle (generator mode). During the motoring mode, current is drawn from the battery (discharging) and during generation mode current is supplied to the battery (charging).

When the APU is on, the ICE is running at its optimum speed and the induction generator charges the battery; in the "off" mode, the ICE idles. Thus, the APU is responsible for decreasing the drain on the battery pack, especially during the acceleration phases of the drive cycle. The ICE control is based on a "constant throttle strategy" which was found to be optimum [30].

The system control strategy for a series hybrid is not required to be as complex as the controller for a parallel hybrid since there is only one torque provider. For the series design discussed in the paper, the classic proportional, integral, and derivative (PID) controller [31] is utilized.

The sizes of the components for the series hybrid drive train are stated in Table III.

D. Electric Drive Train Design

In EV's, all of the onboard systems are powered by batteries and electric motors. The electric drive train designed using V-Elph is shown in Fig. 7.

In the EV, all the torque demanded at the drive wheels is solely met by a vector-controlled induction motor powered by a dc battery pack of 240 V. The controller demands a torque (positive or negative) from the induction motor, depending upon the torque demanded by the vehicle to meet the drive cycle speed. The induction motor tries to meet this demanded torque. Positive power is demanded from the induction motor (operating in motoring mode) during acceleration and cruise phases of the drive cycle and negative power is demanded during the deceleration phase of the drive cycle (operating in generator mode). During the motoring phase the induction motor draws current from the battery pack (discharging) and during the generator mode the induction motor supplies current

TABLE IV
COMPONENTS OF ELECTRIC VEHICLE DRIVE TRAIN

Motor	Vector controlled, 40 kW
Battery	20, 12-volt, lead acid cells in series, 85 A•h per cell

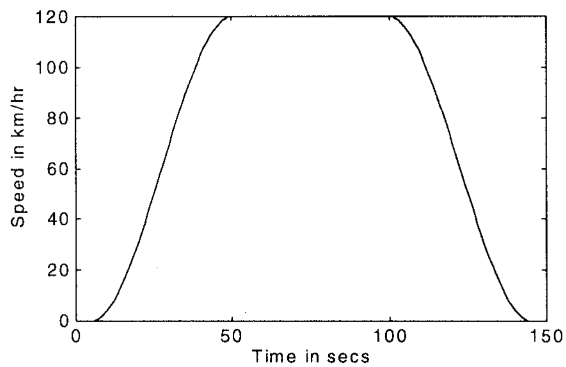


Fig. 8. Drive cycle one consisting of acceleration, cruise, and deceleration.

to it (recharging). The induction motor and battery pack are sized to satisfy the peak power requirements of the drive cycle.

The sizes of the components for the EV drive train are stated in Table IV.

IV. SIMULATION STUDIES

To illustrate the performance potential of new technology vehicles such as electric and hybrid EV's, an electric, parallel HEV, and series HEV were designed using the V-ELPH package. Since the engine model and motor model were not fine-tuned to a set of physical components, the simulation results have some inaccuracies. The authors, therefore, designed a conventional ICE-driven vehicle to serve as the baseline vehicle. Then instead of attaching significance to the exact simulation results, the performance of the new technology vehicles is interpreted in comparison to the baseline vehicle.

Four drive cycles were applied to the various vehicle drive train designs. Drive cycle one consisted of a gradual acceleration to 120 km/h, cruise, and then a deceleration back to stop as shown in Fig. 8. Drive cycles two and three were composed of the FTP-75 urban drive cycle and the federal highway drive cycle [32] as shown in Figs. 9 and 10, respectively. Drive cycle four was a commuter drive cycle as shown in Fig. 11 which was developed by combining three FTP-75 urban drive cycles with two federal highway drive cycles. The two highway cycles are interspaced between each of the urban cycles.

The V-Elph package includes plotting tools that provide graphical displays of output variables generated during simulation studies. Also, V-Elph provides a mechanism to facilitate the study of various aspects related to electric and hybrid EV drive train design such as control strategies and vehicle configurations (e.g., EV and HEV). The following figures illustrate the results of various simulation studies conducted using the four drive cycles with the five vehicle configurations.

Fig. 12 shows a plot of electric motor (EM) torque and ICE torque versus time for the drive cycle one applied to the

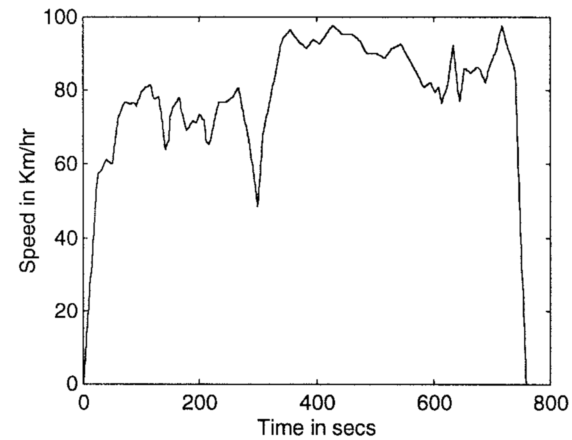


Fig. 9. FTP-75 urban drive cycle—drive cycle two.

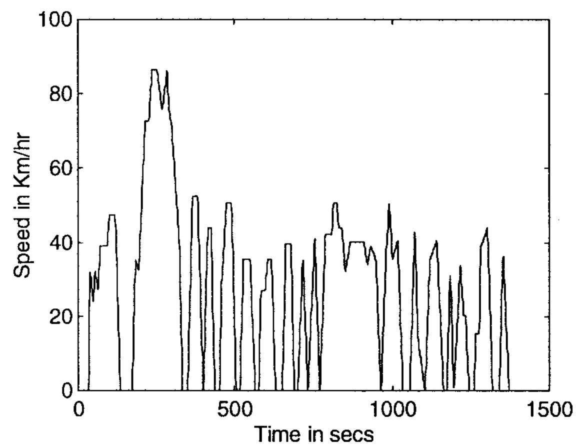


Fig. 10. Federal highway drive cycle—drive cycle three.

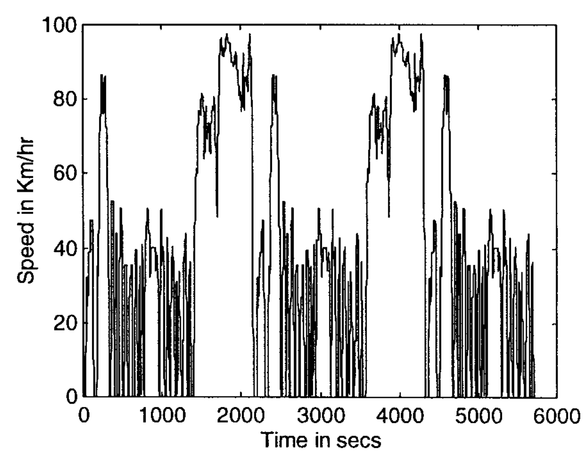


Fig. 11. Commuter drive cycle—drive cycle four.

parallel vehicle using control strategy 1. It illustrates how the electric motor torque increases with the increase in vehicle speed. When the vehicle reaches cruising speed, the electric motor torque reduces to a slightly negative constant value while the ICE torque maintains a constant value. Then during the deceleration phase of the drive cycle, the ICE torque is at its idling torque while the electric motor torque is providing a negative torque, operating in generating mode.

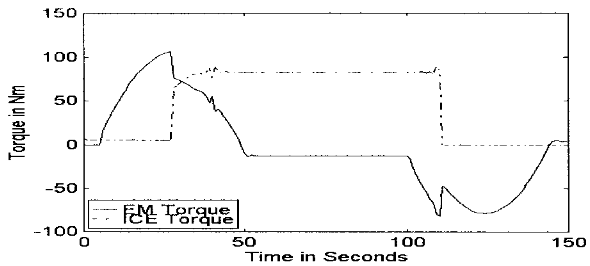
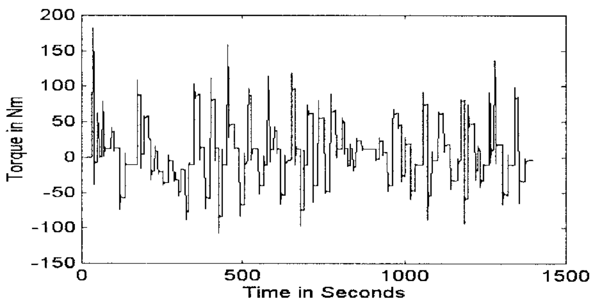
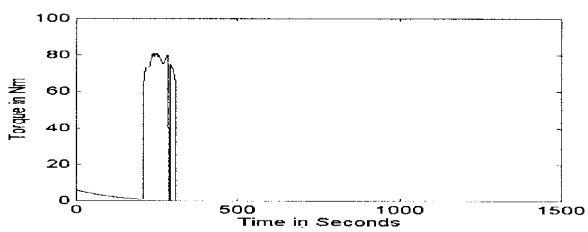


Fig. 12. EM torque and ICE torque for drive cycle one applied to the parallel vehicle with control strategy 1.



(a)



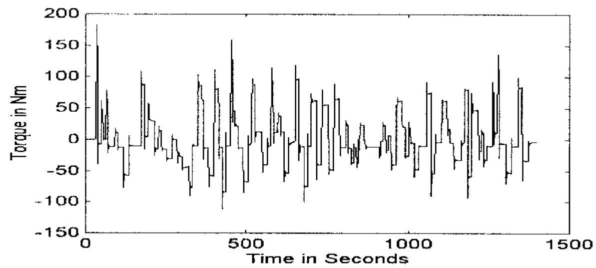
(b)

Fig. 13. (a) EM torque for federal urban drive cycle applied to parallel vehicle with control strategy 1. (b) ICE torque for federal urban drive cycle applied to parallel vehicle with control strategy 1.

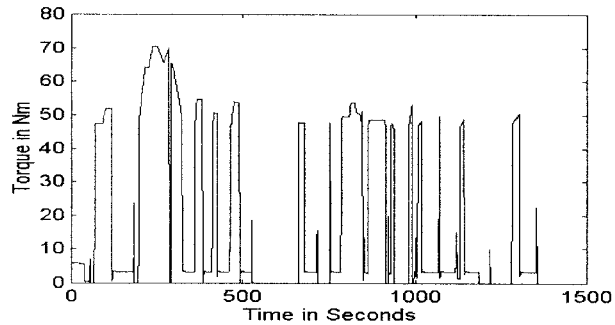
Fig. 13 and 14 show the split of the ICE and electric motor torque for control strategies 1 and 2.

Fig. 15 and 16 show the EM torque for the federal urban drive cycle applied to the series hybrid EV and EV which are similar because for both vehicles the electric machine is the sole source of propulsion. In Figs. 17 and 18, the differences in the battery current for the two test cases are illustrated; the battery current is larger for the EV than the series HEV.

Table V shows a summary of results generated by the V-Elph package during the application of the four drive cycles to the five vehicle drive trains. The weight and control complexity is included in the table for each vehicle drive train. The control complexity was determined by assessing the complexity of the system controller used to manipulate the components providing propulsion to the wheels, e.g., the controller for the parallel HEV controls the ICE and electric machine. For each drive cycle the following parameters were tabulated: the total chemical emissions and fuel consumption of the engine and the amount of energy supplied or depleted by the batteries. A negative value for the amount of energy represents energy depleted and a positive value for the amount of energy represents energy supplied to the batteries. Complex equations



(a)



(b)

Fig. 14. (a) EM torque for federal urban drive cycle applied to parallel vehicle with control strategy 2. (b) ICE torque for federal urban drive cycle applied to parallel vehicle with control strategy 2.

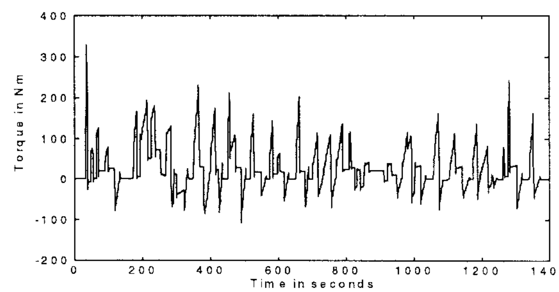


Fig. 15. EM torque for federal urban drive cycle applied to series HEV.

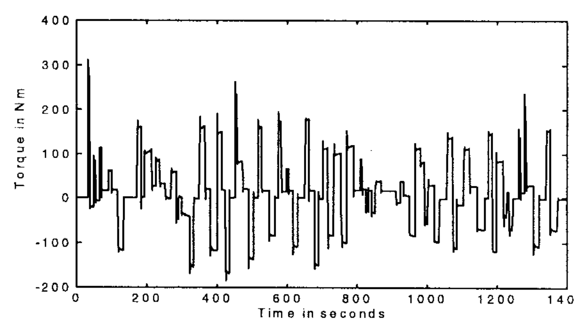


Fig. 16. EM torque for federal urban drive cycle applied to EV.

developed by Ramachandra in 1975 [33] are implemented in the V-Elph package to compute the emissions. The fuel consumption is computed as the total distance traveled divided by the total fuel consumed during the drive cycle. A fuel rate is computed based on work by Powell [29] and then integrated over the time of the drive cycle to yield the fuel consumed.

General observations of the comparison of the conventional vehicle to the new technology vehicles show that: the fuel consumption improved for each of the HEV's which yielded a

TABLE V
COMPARISONS BETWEEN VARIOUS VEHICLE DRIVE TRAIN CONFIGURATIONS

	Conventional	Parallel HEV control strategy 1	Parallel HEV control strategy 2	Series HEV	EV
control complexity	NA	complex	complex	medium	simple
weight (kg)	1700	1838	1838	1908	2008
Drive Cycle One					
NOx (g/km)	2.451	1.447	1.421	2.096	NA
CO (g/km)	1.637	0.6125	0.6198	0.8544	NA
HC	0.03382	0.003336	0.00624	0.001963	NA
fuel consumption (km/l)	7.723	18.96	18.6	20.1	NA
amount of energy supplied or depleted (MJ)	NA	+0.256	+0.143	-0.40	-2.75
Drive Cycle Two: FTP-75 urban drive cycle					
NOx (g/km)	1.314	0.1875	0.3268	1.516	NA
CO (g/km)	1.994	0.1509	0.4926	0.6489	NA
HC	0.08234	0.01036	0.04289	0.01095	NA
fuel consumption (km/l)	5.808	56.02	21.18	19.68	NA
amount of energy supplied or depleted (MJ)	NA	-2.67	-0.258	-2.82	-5.57
Drive Cycle Three: Federal highway drive cycle					
NOx (g/km)	0.7071	1.04	0.86	1.574	NA
CO (g/km)	0.9732	0.7248	0.6528	0.6532	NA
HC	0.05544	0.02907	0.02962	0.002272	NA
fuel consumption (km/l)	12.4	16.5	17.23	21.89	NA
amount of energy supplied or depleted (MJ)	NA	+4.77	+5.11	-4.65	-7.3
Drive Cycle Four: Commuter drive cycle					
NOx (g/km)	0.955	0.6304	0.6195	1.642	NA
CO (g/km)	1.439	0.4491	0.5907	0.6852	NA
HC	0.07379	0.01915	0.03665	0.005872	NA
fuel consumption (km/l)	6.228	24.75	18.69	20.36	NA
amount of energy supplied or depleted (MJ)	NA	+2.0	+8.75	-16.34	-30.76

reduction in emissions. In generally comparing the EV to the HEV's, the battery usage was less.

The results for the urban drive cycle, which is composed of many quick acceleration and deceleration instances, show an improvement in the fuel consumption for the parallel HEV and series HEV compared to the conventional vehicle. Also the engine emissions were greatly reduced. From Figs. 15 and 16, it was noted earlier that the EM torque are very similar for the federal urban drive cycle applied to the series HEV and EV. However, the difference in their change in the battery usage are due to the inclusion of the ICE in the series HEV which uses this fuel source to provide power to recharge the batteries.

The strategy of the controller for the parallel HEV using control strategy 1 was to minimize the use of the ICE. Fig. 13(a) and (b) shows the division of the ICE and EM torque for the urban drive cycle applied to the parallel vehicle drive train using control strategy 1. The ICE torque is only generated when the demanded vehicle speed is greater than 60 km/h. Hence, the motor provides most of the power to the wheels during the drive cycle. This behavior can be seen by comparing the energy usage for the series HEV of 2.82 MJ

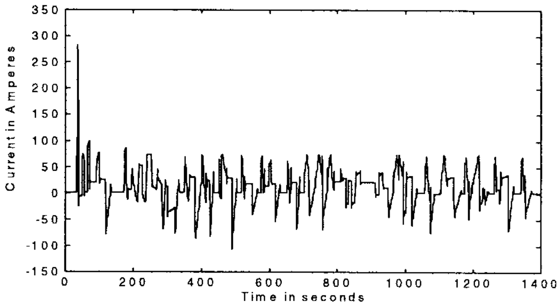


Fig. 17. Battery current for federal urban drive cycle applied to series HEV.

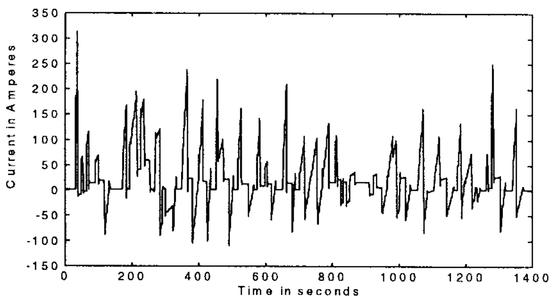


Fig. 18. Battery current for federal urban drive cycle applied to EV.

and for the parallel HEV using control strategy 1 of 2.67 MJ which shows that the motor in the parallel HEV is used almost as much as the motor in the series HEV. Thus, the fuel consumption (km/l) for the parallel HEV using control strategy 1 is extremely large due to the minimal usage of the ICE.

Minimization of the ICE throttle is the control strategy for the parallel HEV using control strategy 2. The ICE throttle position is determined using the steady-state load (aerodynamic drag and friction) required at a particular vehicle speed. In comparing the performance of this drive train using the urban and highway drive cycles, the fuel consumption, the kilometers traveled per liter, for the urban cycle is greater because the motor is used more during the urban cycle than the highway cycle.

Furthermore, the differences in the performance of the two control strategies for a parallel HEV are also illustrated by comparing the fuel consumption and energy usage of the parallel HEV's for the federal urban drive cycle.

Since the battery pack is the sole power supplier in the EV, its energy usage is greater than the parallel or series hybrid vehicles, as expected.

V. CONCLUSION

This paper discussed a new drive train modeling, simulation, and analysis package developed at Texas A&M University using Matlab/Simulink to study issues related to EV and HEV design such as energy efficiency, fuel economy, and vehicle emissions. The package uses visual programming techniques, allowing the user to quickly change architectures, parameters, and to view output data graphically. It also includes detailed models of electric motors, internal combustion engines, and batteries. The designs for four vehicle drive trains—an EV, parallel HEV, series HEV, and conventional ICE vehicle—are presented. The results of applying simple, commuter, federal urban, and federal highway drive cycles are compared. These results illustrate the flexibility of the package for studying various issues related to electric and hybrid EV design. The simulation package can run on a PC or a Unix-based workstation.

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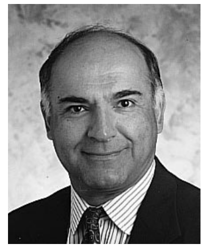

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