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A study on optimization of hybrid drive train using Advanced Vehicle Simulator (ADVISOR)

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ABSTRACT

This study investigates the advantages and disadvantages of three hybrid drive train configurations: series, parallel, and "through-the-ground" parallel. Power flow simulations are conducted with the MATLAB/Simulink-based software ADVISOR. These simulations are then applied in an application for the UC Davis SAE Formula Hybrid vehicle. ADVISOR performs simulation calculations for vehicle position using a combined backward/forward method.

These simulations are used to study how efficiency and agility are affected by the motor, fuel converter, and hybrid configuration. Three different vehicle models are developed to optimize the drive train of a vehicle for three stages of the SAE Formula Hybrid competition: autocross, endurance, and acceleration. Input cycles are created based on rough estimates of track geometry. The output from these ADVISOR simulations is a series of plots of velocity profile and energy storage State of Charge that provide a good estimate of how the Formula Hybrid vehicle will perform on the given course. The most noticeable discrepancy between the input cycle and the actual velocity profile of the vehicle occurs during deceleration.

A weighted ranking system is developed to organize the simulation results and to determine the best drive train configuration for the Formula Hybrid vehicle. Results show that the through-the-ground parallel configuration with front-mounted motors achieves an optimal balance of efficiency, simplicity, and cost.

ADVISOR is proven to be a useful tool for vehicle power train design for the SAE Formula Hybrid competition. This vehicle model based on ADVISOR simulation is applicable to various studies concerning performance and efficiency of hybrid drive trains.

1. Introduction

Due to the increasing rate of global petroleum consumption, there is a critical need to develop more efficient power generation systems for the transportation sector. Hybrid gasoline-electric vehicles are garnering more attention with a global energy crisis looming in the next decade. Hybrid vehicle technology involves more complex power train design than traditional gasoline-powered vehicles. The cost of hybrid drive train design can be mitigated by utilizing vehicle simulators to predict the performance of the vehicle and its onboard subsystems under a variety of driving conditions [1].

Simulations are particularly useful for the automotive industry, but can also be applied to academic projects. Competitions are held annually by the Society of Automotive Engineers (SAE) challenging university students to design, build, and race high performance vehicles. Reacting to heightened interest in more fuel-efficient vehicles, SAE has introduced the Formula Hybrid competition [2], which is based on the traditional Formula SAE International competition with an added emphasis on fuel efficiency. The competition provides undergraduate engineering students the opportunity to study the relationship between efficiency and performance on a small scale.

This study will demonstrate the application of Advanced Vehicle Simulator (ADVISOR) software to hybrid drive train configuration optimization for a Formula Hybrid International Competition vehicle. ADVISOR was developed by the National Renewable Energy Laboratory (NREL) to aid in the development of alternatively powered vehicles. It was intended to ease the numerical simulation process for vehicles under development.

Previous research has shown the utility of the ADVISOR program. Wipke et al. [3] presented the design of the ADVISOR software, explained its combined backward–forward calculation approach and demonstrated its accuracy, speed, and flexibility. Markel et al. [4] provided a practical overview of ADVISOR, including the layout of the graphical user interface (GUI), capabilities and

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Nomenclature

ADVISOR	Advanced Vehicle Simulator
SAE	Society of Automotive Engineers
NREL	National Renewable Energy Laboratory
GUI	Graphical User Interface
SOC	State of Charge
RC	resistance-capacitance
NiMH	nickel-metal hydride
AWD	all wheel drive
RDW	rear wheel drive

limitations of the program, and power source modeling options. Further, Johnson [5] summarized battery modeling capabilities in ADVISOR and demonstrated that a resistance–capacitance (RC) model is preferred for vehicle simulations. Myers [6] applied tools in the Simulink environment to model a hybrid drive train for a postal service delivery vehicle. Sørensen [7] utilized the ADVISOR program to analyze a basic vehicle used for studying hybrid fuel cell/battery passenger cars. Finally, Wang and Bai [8] modified the parallel block diagram in ADVISOR to develop a simple electric vehicle ("ELVEC"). The vehicle required specific controls and components not provided in the software. Wang and Bei found the simulation and results analysis tools to be convenient and useful in proving the capabilities of their design. Our use of ADVISOR in a competitive setting appears to be unique compared to previous research.

We applied ADVISOR to compare three hybrid drive train configurations (series, parallel, and "through-the-ground") based on overall efficiency and energy consumption. Three different drive cycles were used to simulate the top speed, endurance, and autocross portions of the Formula Hybrid competition. Although the vehicle described herein was designed and built according to the specific requirements of the Formula Hybrid competition, the application of ADVISOR to drive train optimization can be extended to general vehicle design.

2. ADVISOR structure and capabilities

ADVISOR was created in the MATLAB/Simulink environment. The program uses an iterative calculation scheme to generate outputs of a vehicle's velocity and energy use at all times during a given simulation. ADVISOR uses a combined backward/forward method. In a forward-facing approach, operator inputs such as throttle position and braking are defined by a driver model based on the desired speed. These inputs are used to calculate the required torque and energy use rate of the vehicle drive train. The computation proceeds forward from the engine, through the transmission and to the wheels, finally resulting in calculation of a tractive force at the tire/road interface. The forward-facing approach is desirable for hardware development and detailed control simulation, but the simulation speed is slow. A pure forward approach is too time-consuming for preliminary design. A simplified block diagram of a generic forward-facing simulation approach is presented in Fig. 1.

In contrast to the forward-facing approach, which begins with a driver model, a backward-facing approach is driven by the required vehicle velocity. The backward-facing approach does not include a driver model. The force required to accelerate the vehicle through the time step is calculated directly from the speed trace of the driving cycle that is being simulated. The simulation determines the torque and speed of drive train components that is necessary to overcome the inertial forces of the vehicle and reach the desired velocity. The calculation proceeds backwards from the tire/road interface through the drive train, ending with the energy source (typically an internal combustion engine and fuel tank). The backward-facing approach allows for simple and fast calculation, but is not useful for studying control systems due to the lack of throttle and brake information. Because the backward-facing model assumes that the vehicle meets the required speed trace, a pure backward approach is not suited to analyze best-effort performance (i.e., acceleration tests). A simplified block diagram of a generic backward-facing simulation approach is presented in Fig. 2.

By combining the forward- and backward-facing methods, ADVISOR can take advantage of advanced battery and component models effectively while maintaining a relatively fast simulation speed.

The user manipulates a series of GUI screens to input various vehicle parameters and drive cycle requirements and monitor their impact on vehicle performance, fuel economy, and emissions. The three main GUI screens in ADVISOR are the vehicle input screen, the simulation setup screen and the results screen. Examples of these screens are shown in Fig. 3a–c. In the vehicle input screen (Fig. 3a), the user builds a vehicle of interest by selecting options from a series of drop-down menus. Each list includes several preprogrammed parts for use in the vehicle. The user may also create custom components by editing the properties of each part. This feature makes ADVISOR convenient for innovative vehicle design and simulation. In the simulation setup screen (Fig. 3b), the user defines the drive cycle parameters for the event over which the vehicle is to be simulated. Vehicle performance can be reviewed in the results screen (Fig. 3c), where fuel economy and emissions are displayed alongside detailed plots of time-dependent outputs. The user can select from a wide array of output options related to speed and torque, fuel consumption, emissions, battery charge level, etc., and display up to four plots simultaneously.

3. Drive train configurations

The two main configurations used in modern gasoline-electric hybrid vehicles are the series and parallel configurations. A series hybrid configuration uses the gasoline engine for electrical energy generation while an electric motor provides full propulsion to the wheels. Fig. 4 represents a typical series hybrid configuration. The batteries provide a relatively constant supply of power in a series configuration, but some variation in the State of Charge (SOC) occurs during driving. Packaging and control systems for a series hybrid are relatively simple because there is no direct mechanical coupling between the engine and the vehicle drive, and therefore no need for clutches. In lieu of a conventional transmission, the control systems alter the amount of current to the motor, which controls the torque applied to the wheels. The battery pack in a series configuration is large because it must accommodate peak power requirements during driving. This makes a series hybrid configuration more expensive than a parallel configuration.

Parallel hybrid systems are more common in present production vehicles. A parallel configuration includes a large electrical generator and motor combined in a single unit, often located between the combustion engine and the transmission. Fig. 5 represents a typical parallel hybrid configuration. A high-voltage battery pack stores energy from the generator. The most common parallel hybrid motor configurations utilize a belt drive or a mechanical gearing arrangement in which the motor may be integral with the engine, replacing the normal flywheel. This allows power from the internal combustion engine, the electrical motor, or both, to move the vehicle.

A third option for the Formula Hybrid vehicle is a through-the-ground configuration. Power production is shared between electric motors and the internal combustion engine, with the

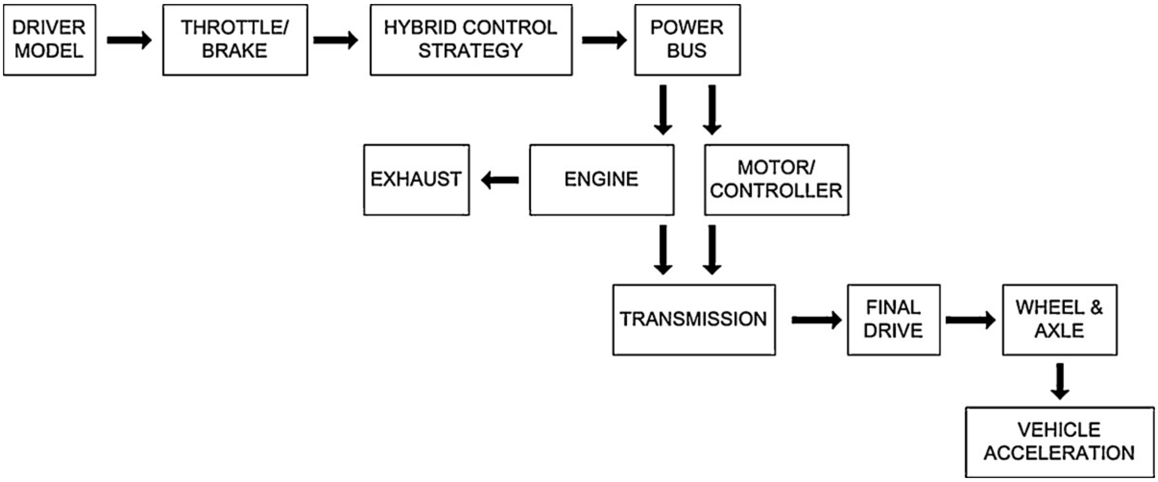


Fig. 1. Generic forward-facing calculation approach.

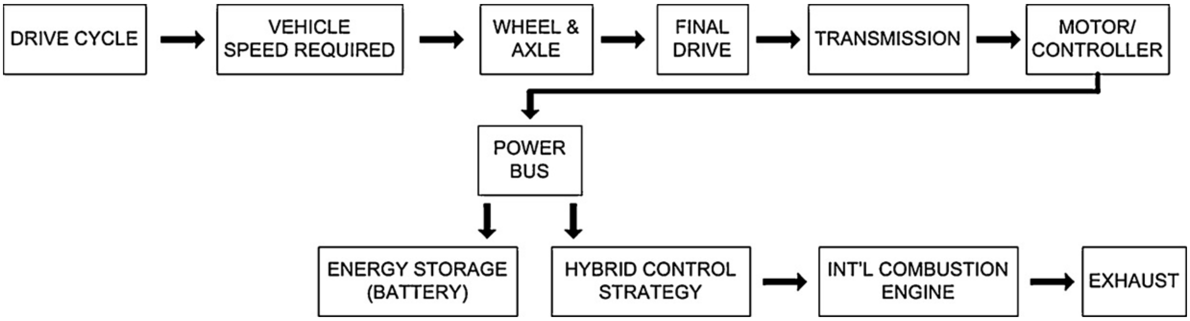


Fig. 2. Generic backward-facing calculation approach.

motors located downstream of the transmission, just before the vehicle's wheels. A single electric motor can drive both wheels on an axle using drive shafts, or two individual electric motors can be used, with one mounted at each wheel. Fig. 6 illustrates the latter configuration. The motors can either be chassis-mounted or hub-mounted. Hub-mounted motors eliminate the need for a front end differential and driveshaft. The through-the-ground configuration involves the same power flows and component requirements as a parallel hybrid system, but requires additional controls to provide the differential when cornering. The technology for hub-mounted motors has not matured to the point of feasibility for the Formula Hybrid vehicle. A similar effect can be achieved by placing an electric motor in the front to power the front wheels. As the Formula Hybrid competition has strict rules concerning crumple zones, a front-mounted motor would require careful design to comply with safety regulations.

4. Vehicle models and parameters

Figs. 7 and 8 show the Simulink control systems for series and parallel configurations, respectively. These block diagrams represent how ADVISOR applies the drive cycle and vehicle properties (such as inertial forces and frictional forces due to drag and rolling resistance) to analyze the power flow. ADVISOR applies a dynamic gain to determine whether the desired power flow can be provided to each element represented in the block diagram. Through discrete time step solution methods, Simulink is able to solve the characteristic differential equations of the system.

Table 1
Fuel converter specification table.

	Engine specifications	
	Series	Parallel
Model	Subaru Robin EX21	Kawasaki Ninja 250R
Displacement	211 cm^3	249 cm^3
Maximum power	5.1 kW at 4000 RPM	26.85 kW at 11000 RPM
Maximum torque	13.9 Nm at 2500 RPM	22 Nm at 9500 RPM
Maximum RPM	4000	15000

Table 2
Electric motor specifications at 72 V.

	Motor specifications	
	Series generator	Parallel/series drive motor
Model	Perm PMG 132	NetGain WarP 9
Maximum power	25.58 kW	28.78 kW
Maximum torque	20.5 Nm	81.26 Nm
Maximum RPM	13000	5500
Mass	11.25 kg	58.5 kg

ADVISOR enables the user to modify many variables in a hybrid vehicle drive train. Each major component in the drive train can be changed independently to simulate different configurations. Our simulation was based on designs from previous Formula Hybrid competitors. The team's power requirement calculations were compared to earlier teams' drive trains to determine the appropriate engines and motors for the simulation. The Subaru Robin EX21 internal combustion engine and Thunderstruck Perm PMG 132 electric motor were selected for the generator system of the series configuration. The NetGain WarP 9 was selected for the series rear drive motor. The NetGain WarP 9 motor and the Kawasaki Ninja 250R two cylinder internal combustion engine were selected for simulation of both the conventional and the "through-the-ground" parallel configurations. Table 1 lists the engine specifications [9,10] and Table 2 lists the motor specifications [11,12] that were used in these simulations.

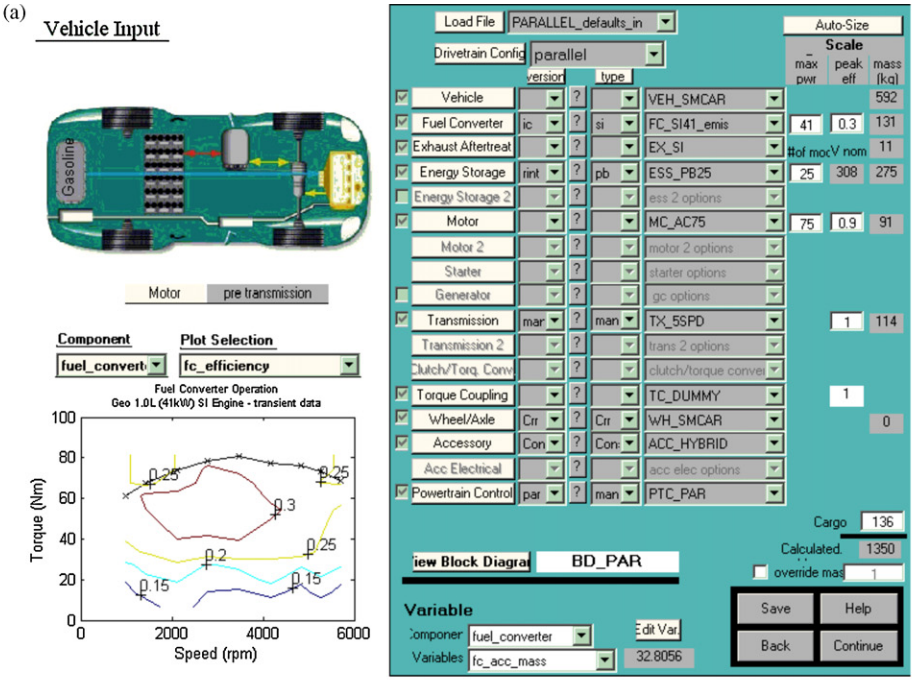
Our objective was to construct a comparison between vehicle configurations, and therefore the values for some non-critical components were held constant at defaults across the three configurations. The following is a summary of the variables that were considered in detail during the simulation.

4.1. Fuel converter

The following variables were adjusted for the fuel converter:

- *Profile selection*: A torque/speed profile that best represented the profile for engines used is selected with this variable.
- *Speed scale*: This variable is adjusted to map the operating range for the given engine.
- *Power scale*: This variable is adjusted to denote the maximum power the engine can transfer.
- *Torque scale*: Speed scale and power scale adjust the torque scale, so there needs to be a trial and error process to adjust each of

(a)



Load File PARALLEL_defaults_in

Drivetrain Config parallel

Component fuel_convert

Plot Selection fc_efficiency

	Component	version	type		max pwr	peak eff	mass (kg)
☑	Vehicle			VEH_SMCAR			592
☑	Fuel Converter	ic	si	FC_SI41_emis	41	0.3	131
☑	Exhaust Aftertreat			EX_SI	#of moc	V nom	11
☑	Energy Storage	rint	pb	ESS_PB25	25	308	275
☐	Energy Storage 2			ess 2 options			
☑	Motor			MC_AC75	75	0.9	91
	Motor 2			motor 2 options			
	Starter			starter options			
☐	Generator			gc options			
☑	Transmission	man	man	TX_5SPD		1	114
	Transmission 2			trans 2 options			
	Clutch/Torq. Conv			clutch/torque conver			
☑	Torque Coupling			TC_DUMMY		1	
☑	Wheel/Axle	Crr	Crr	WH_SMCAR			0
☑	Accessory	Con	Con	ACC_HYBRID			
	Acc Electrical			acc elec options			
☑	Powertrain Control	par	man	PTC_PAR			

Cargo 136

Calculated 1350

☐ override mas 1

iew Block Diagra BD_PAR

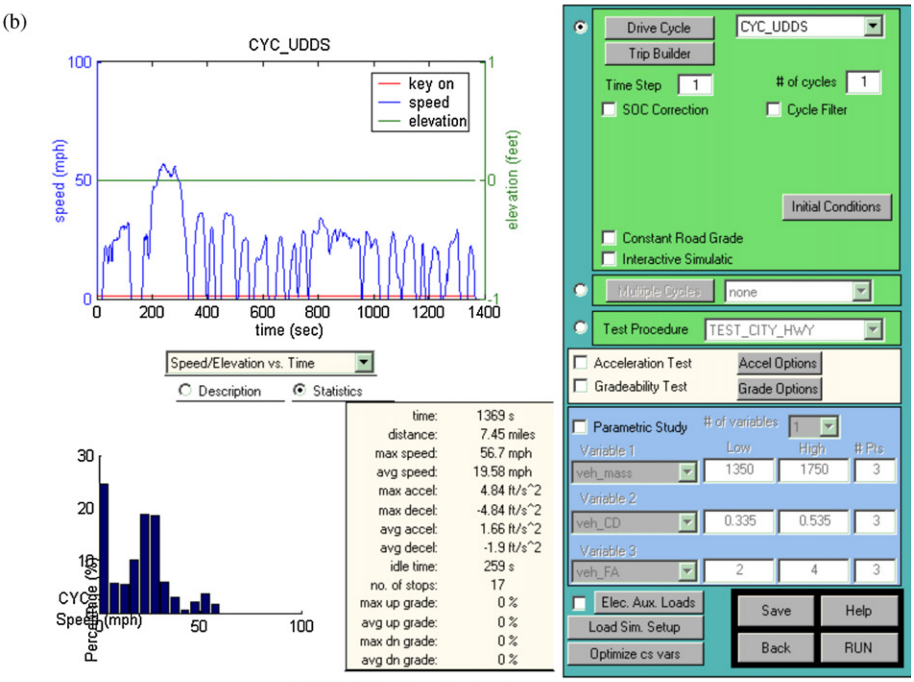
Variable

Componer fuel_converter

Variables fc_acc_mass 32.8056

ADVISOR Vehicle Input screen

(b)



● Drive Cycle CYC_UDDS

Trip Builder

Time Step 1

\# of cycles 1

☐ SOC Correction

☐ Cycle Filter

☐ Constant Road Grade

☐ Interactive Simulatic

○ Multiple Cycles none

○ Test Procedure TEST_CITY_HWY

☐ Acceleration Test

☐ Gradeability Test

☐ Parametric Study # of variables 1

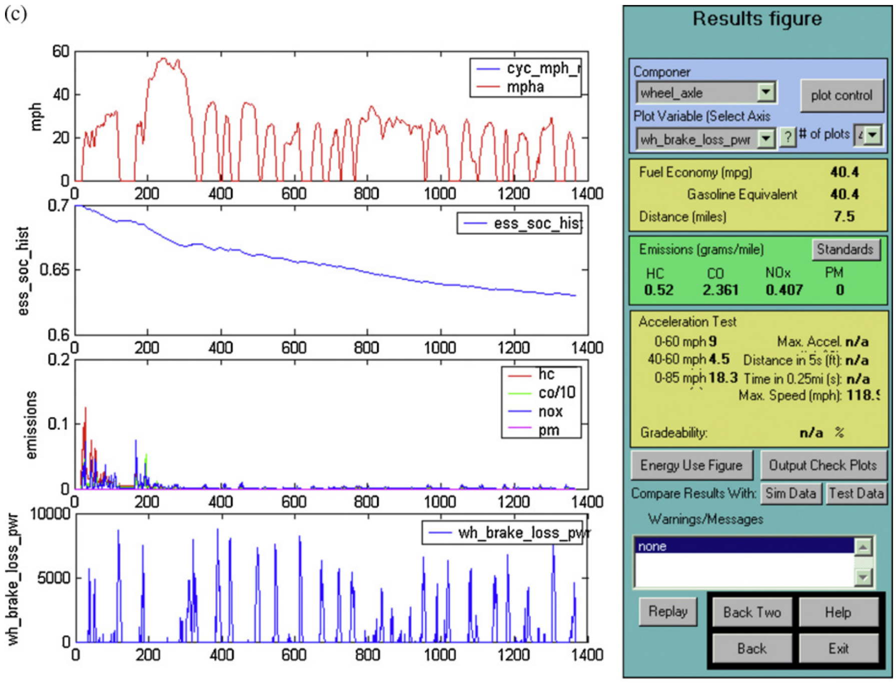
	Low	High	# Pts
Variable 1 veh_mass	1350	1750	3
Variable 2 veh_CD	0.335	0.535	3
Variable 3 veh_FA	2	4	3

☐ Elec. Aux. Loads

time:	1369 s
distance:	7.45 miles
max speed:	56.7 mph
avg speed:	19.58 mph
max accel:	4.84 ft/s^2
max decel:	-4.84 ft/s^2
avg accel:	1.66 ft/s^2
avg decel:	-1.9 ft/s^2
idle time:	259 s
no. of stops:	17
max up grade:	0 %
avg up grade:	0 %
max dn grade:	0 %
avg dn grade:	0 %

ADVISOR Simulation Parameters screen

Fig. 3. (a) ADVISOR vehicle input screen. (b) ADVISOR simulation parameters screen. (c) ADVISOR results screen.



Componer: wheel_axle

Plot Variable (Select Axis: wh_brake_loss_pwr

Fuel Economy (mpg) **40.4**
Gasoline Equivalent **40.4**
Distance (miles) **7.5**

Emissions (grams/mile)

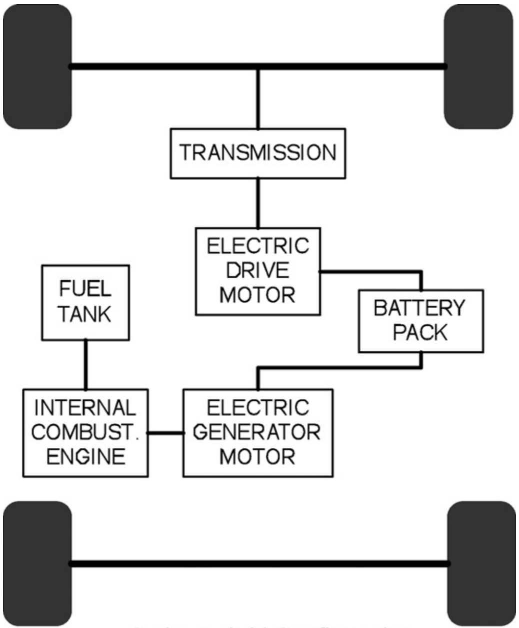
HC	CO	NOx	PM
0.52	**2.361**	**0.407**	**0**

Acceleration Test
0-60 mph **9**
40-60 mph **4.5**
0-85 mph **18.3**
Max. Accel. **n/a**
Distance in 5s (ft): **n/a**
Time in 0.25mi (s): **n/a**
Max. Speed (mph): **118.**
Gradeability: **n/a** %

Warnings/Messages
none

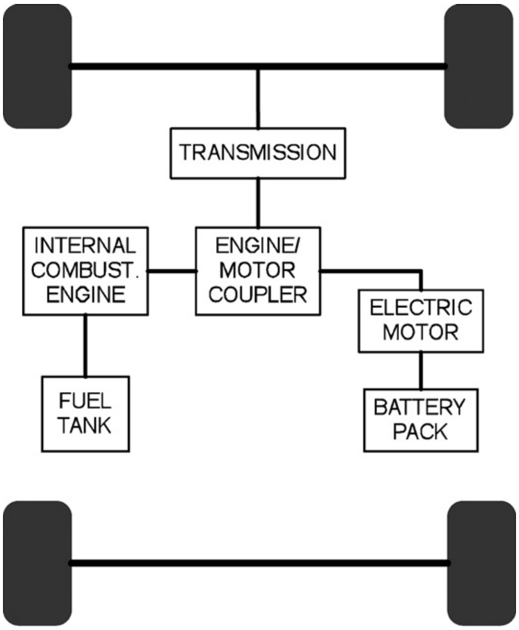
ADVISOR Results screen

Fig. 3. (*Continued*.)



Series Hybrid Configuration

Fig. 4. Series hybrid configuration.



Parallel Hybrid Configuration

Fig. 5. Parallel hybrid configuration.

the variable with respect to one another in order to get a profile closest to the actual engine.

4.2. *Motor/controller*

Modification of profile selection, speed scale, power scale and torque scale is similar to that of the fuel converter described above.

4.3. *Energy storage system*

The energy storage system was set at a constant value for each simulation. The amount of energy spent during the drive cycle was used to determine the required size of the energy banks. A pack of six (6), 12-V lead acid battery model was used for this application.[1]

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[1] Nickel-metal hydride (NiMH) and lithium-ion models also yielded favorable results. However, the cost of purchasing the necessary quantity of NiMH or lithium-ion battery packs and associated cooling systems was found to be prohibitively high for this application, and these chemistries were therefore not considered for the Formula Hybrid vehicle.

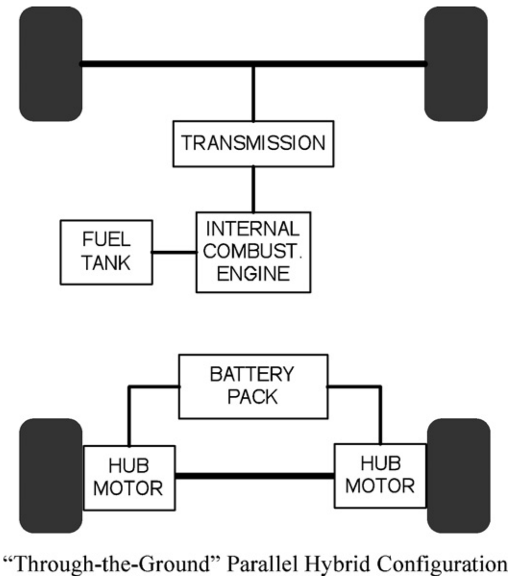

Fig. 6. "Through-the-ground" parallel hybrid configuration.

4.4. *Transmission*

Removal of unnecessary gears (for weight reduction) was considered, until it was determined that the weight of the entire transmission was approximately twenty pounds. The gears in question could be utilized during the endurance circuit to increase fuel economy. We used the factory-sourced 5 gear manual transmission provided with the Ninja 250R engine in its original configuration. In professional racing applications, computer modeling software is available to tailor gear ratios for a specific track. Professional racing teams typically build a custom set of gears for each track on which they compete. It is recommended that this feature is researched and included on future design iterations.

4.5. *Vehicle mass*

Vehicle mass was assumed to be unchanged across the three configurations. The vehicle mass was held constant at 350 kg. This helped to isolate the effects of other variables in simulation.

4.6. *Parallel drive train configuration*

The "through-the-ground" parallel configuration and the conventional parallel system were modeled using the same specifications. All motor and engine variables were held constant across the two parallel configurations. The only parameters that were modified were the weight and energy leaving/entering the motor or engine relative to their connection to the front or rear wheels. This modification accounts for greater regenerative braking in the "through-the-ground" configuration.

4.7. *Velocity profile*

The velocity profile is essential to understanding how a parallel hybrid vehicle will perform. Frequency and amplitude of acceler-

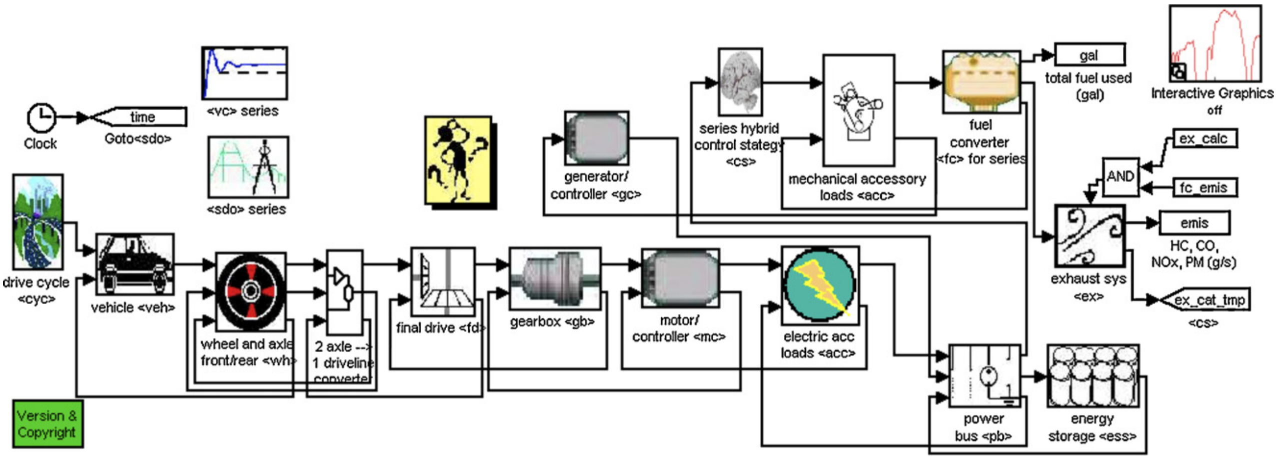

Fig. 7. ADVISOR block diagram – series configuration.

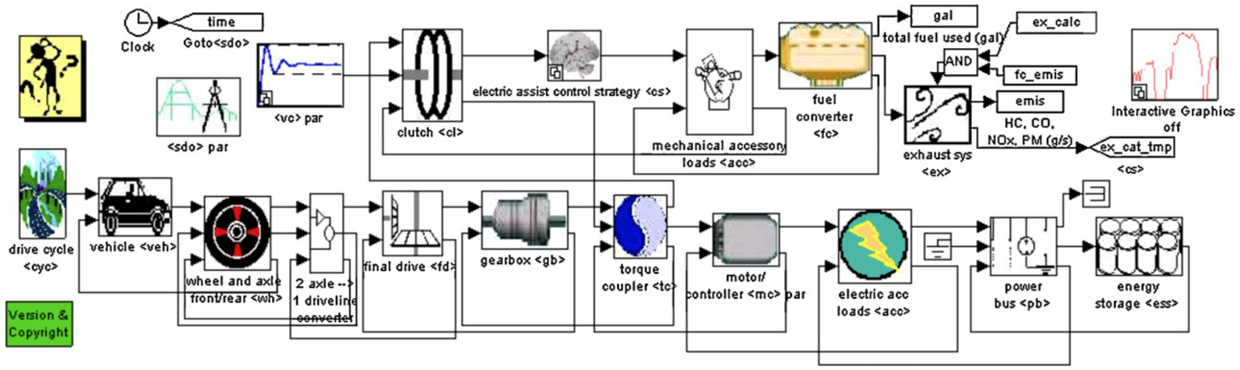

Fig. 8. ADVISOR block diagram – parallel configuration.

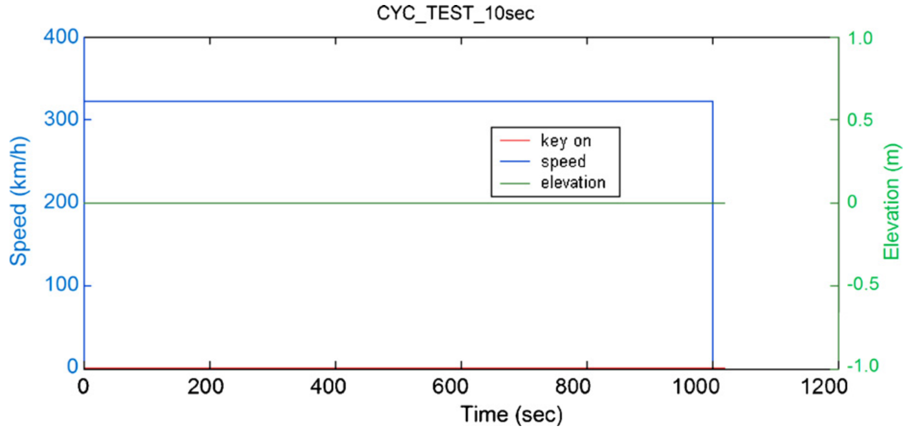

Fig. 9. Acceleration test velocity profile.

Fig. 10. Autocross course satellite image (*courtesy*: Ron Baker).

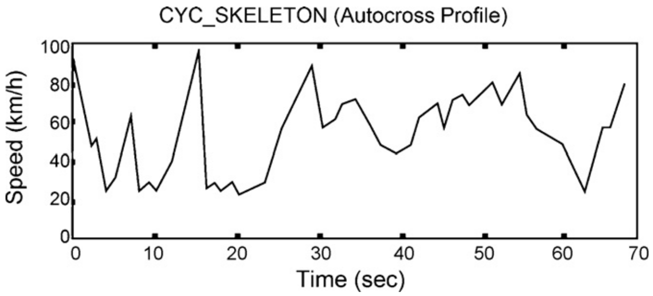

Fig. 11. Autocross velocity profile.

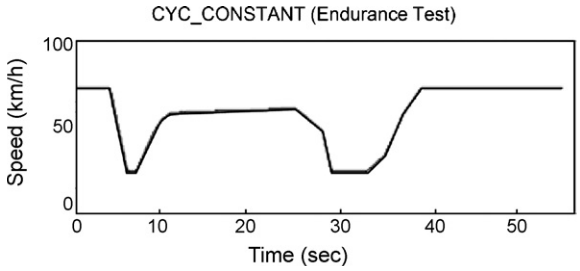

Fig. 12. Endurance velocity profile.

ation and braking can dramatically change the simulation results. Three velocity profiles were created to test the overall acceleration properties, the endurance, and the autocross performance of our vehicle model.

4.8. Acceleration profile

An acceleration profile was generated by creating a velocity profile with a step input from 0 to 200 mph (Fig. 9). A maximum speed of 200 mph is far greater than the feasible top speed of the Formula Hybrid vehicle. This profile therefore creates a best-effort simulation to determine the maximum speed and acceleration of our model.

4.9. Autocross profile

Based on an image of a previous FSAE autocross course (Fig. 10) and meticulously measured distances on the picture, we were able to obtain an approximate velocity profile of the autocross course (Fig. 11).

4.10. Endurance profile

The endurance course is a thin oval shape that allows for acceleration on the sides and the possibility for regenerative braking going into the corners. Fig. 12 shows the velocity profile for one lap around the endurance course. The endurance competition requires 22 laps around the course, so we simulated the endurance course by using 22 consecutive drive cycles.

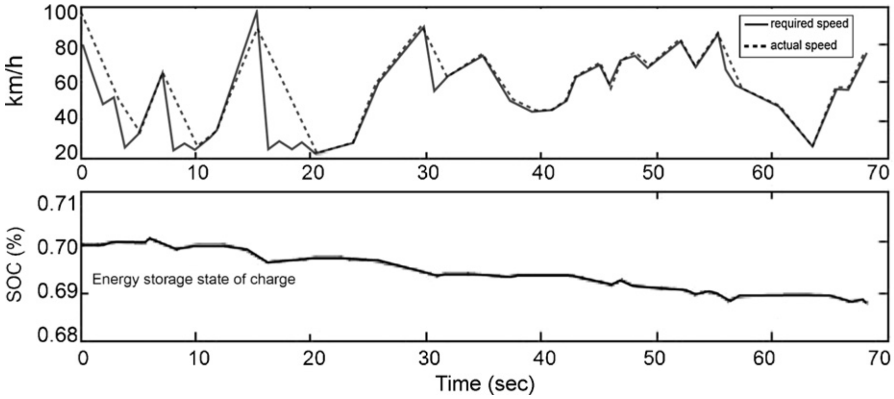

Fig. 13. Series configuration autocross – velocity profile and energy storage State of Charge.

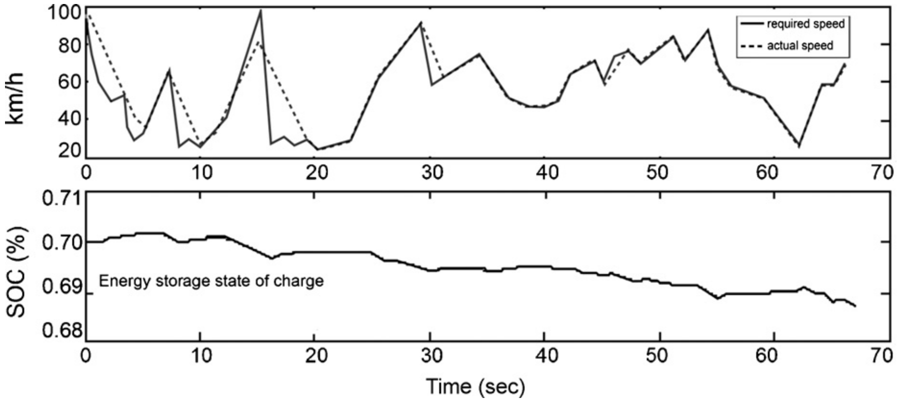

Fig. 14. Parallel configuration autocross – velocity profile and energy storage State of Charge.

After all the pertinent variables were selected and modified, each power train configuration was run on each velocity profile, for a total of nine simulations.

5. Simulation results

The primary outputs from the ADVISOR simulations were plots showing the velocity profile and State of Charge as a function of time over the course of a lap in the Autocross competition. Fig. 13 shows the results for the series hybrid configuration; Fig. 14 represents the parallel hybrid configuration, and Fig. 15 represents the "through-the-ground" parallel hybrid configuration. The top graphs display the input drive cycle against the actual simulated velocity of the vehicle. The bottom graphs display the State of Charge of the energy storage system. These profiles provide a good estimate of how the Formula Hybrid vehicle will perform on the given course. There was a noticeable discrepancy between the input deceleration and the actual deceleration of the vehicle. This was initially attributed to the maximum deceleration allowed by the coefficient of rolling friction. However, based on a coefficient of friction of 0.8, the maximum acceleration or deceleration is 12.1 m s^{-2}. ADVISOR does not model conventional brakes, but instead uses only a regenerative braking model to slow the vehicle. Modifying the MATLAB files associated with deceleration was beyond the scope of the Formula Hybrid project, and this discrepancy in deceleration was therefore accepted.

ADVISOR provides a detailed summary of the energy flow in and out of each of the vehicle power train elements. The most relevant

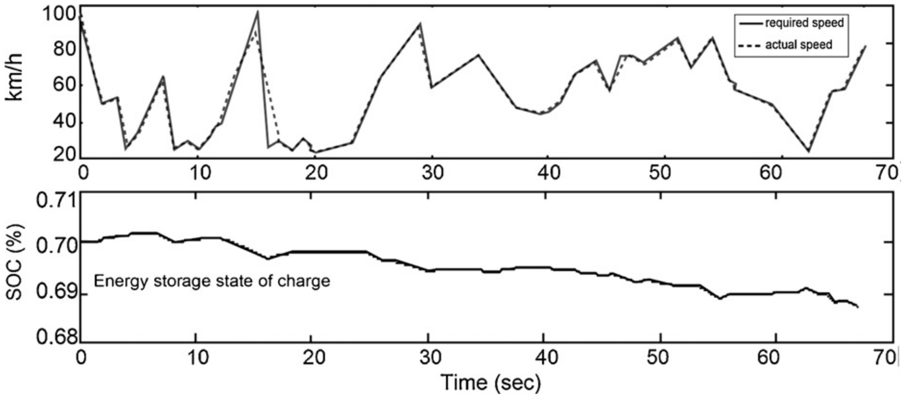

Fig. 15. Through-the-ground configuration autocross – velocity profile and energy storage State of Charge.

Table 3
ADVISOR simulation outputs: autocross, endurance, and acceleration courses.

	ADVISOR simulation outputs Parallel – autocross RWD	AWD	Series – autocross RWD
Energy storage out (kJ)	527	540	818
Energy storage in (kJ)	237	310	280
Energy Diff. [out – in] (kJ)	290	230	538
Overall system efficiency	0.09	0.074	0.245
Ahs. Avg. Diff. (mph)	2.3021	0.657	2.3276
% Trace miss	23.13	6.71	21.64
	Parallel – endurance		Series –endurance
	RWD	AWD	RWD
Energy storage out (kJ)	2227	2315	5739
Energy storage in (kJ)	806	1100	642
Energy Diff. [out – in] (kJ)	1421	1215	5097
Overall system efficiency	0.098	0.098	0.352
Abs. Avg. Diff. (mph)	0.1439	0	0.144
% Trace miss	3.58	0	3.58
	Parallel – acceleration		Series – acceleration
	RWD	AWD	RWD
Unrestricted 75 m (s)	5.7	5.1	5.6
Electrical 75 m (s)	5.9	5.5	5.6

Note: In the parallel category, "RWD" represents the conventional parallel configuration and "AWD" represents "through-the-ground" parallel configuration.

data for the Formula Hybrid competition are the amount of energy drawn from the batteries, overall system efficiency, and agility of the vehicle as judged by how closely the actual velocity profile matches the input velocity profile. These results are summarized in Table 3.

A weighted ranking system was developed to determine the optimal configuration for the Formula Hybrid vehicle. The ranking system was based on the following Formula SAE competition point breakdown:

- Autocross competition: 150 points
- Endurance competition: 400 points
- Acceleration competition: 150 points

Each section was then further broken down into sub-categories and weighted accordingly. For the Autocross competition, the sub-categories were weighted as: battery use – 30%; efficiency – 10%; agility-1 and agility-2 – 40% each. For the Endurance competition, the sub-categories were weighted as: battery use – 45%; efficiency – 45%; agility-1 and agility-2–40% each. For the Acceleration competition, unrestricted acceleration and electric acceleration were each weighted at 50%.

Table 4
Weighted rankings from ADVISOR output.

	Parallel (RWD)	Parallel (AWD)	Series
Autocross (150 points)			
Battery use (30%)	35.69	45.00	19.24
Efficiency (10%)	5.51	4.53	15.00
Agility 1 (40%)	17.12	60.00	16.94
Agility 2 (40%)	17.41	60.00	18.50
Total autocross	75.73	169.53	69.78
Endurance (400 points)			
Battery use (45%)	153.91	180.00	42.91
Efficiency (45%)	50.11	50.11	180.00
Agility 1 (40%)	6.95	20.00	6.94
Agility 2 (40%)	5.59	20.00	5.59
Total endurance	216.56	270.11	235.44
Acceleration (150 points)			
Unrestricted (50%)	67.11	75.00	68.30
Electric (50%)	69.92	73.66	73.66
Total acceleration	137.02	148.66	141.96
Total score	429.31	588.30	447.18

Maximum points were awarded to the configuration with the best performance in each category, and a proportional amount of points was pro-rated for the second- and third-best configurations. The parallel (AWD) configuration was found to be optimal based on the developed weighted rankings from ADVISOR simulations. Table 4 shows that the "through-the-ground" configuration yields the highest weighted score out of the three options.

6. Conclusions

ADVISOR is a mathematical modeling tool that is useful for vehicle power train design. This application demonstrates the utility of ADVISOR when applied to a gasoline-electric hybrid vehicle tailored to the SAE Formula Hybrid competition guidelines. A weighted ranking system of results from ADVISOR is developed to determine the optimal hybrid configuration for the Formula Hybrid competition. Simulation results indicate that a "through-the-ground" parallel system, consisting of an electric motor to drive the front wheels and an internal combustion engine to power the rear, is the best for this application.

The NetGain Warp9 motor is recommended for this application because of its sufficient power output and affordable price. The Kawasaki Ninja 250R engine is recommended. Factory transmission gearing is sufficient for this student project, although custom transmission gearing would be preferred in a professional competitive environment. Six 12-V lead acid batteries are sufficient for robust acceleration. Future testing on the energy storage system is recommended. Finally, the favorable simulation results for the "through-the-ground" parallel hybrid configuration suggest that hub motors will be a viable option to future SAE Formula Hybrid teams as the technology matures. Computer simulations for optimization of drive train design, as described in this study, can potentially be applied to other areas of academics and industry.

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