Using an Advanced Vehicle Simulator (ADVISOR) to Guide Hybrid Vehicle Propulsion System Development

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Abstract

An advanced vehicle simulator model called ADVISOR has been developed at the National Renewable Energy Laboratory to allow system-level analysis and trade-off studies of advanced vehicles. Because of ADVISOR's fast execution speed and the open programming environment of MATLAB/Simulink, the simulator is ideally suited for doing parametric studies to map out the design space of potential high fuel economy vehicles (3X) consistent with the goals of the Partnership for New Generation of Vehicles (PNGV). Five separate vehicle configurations have been modeled including 3 lightweight vehicles (parallel, series, and conventional drivetrains) along with 2 vehicles with 1996 vehicle weights (parallel and conventional drivetrains). The sensitivity of each vehicle's fuel economy to critical vehicle parameters is then examined and regions of interest for the vehicles mapped out through parametric studies. Using the simulation results for these vehicles, the effect of hybridization is isolated and analyzed and the trade-offs between series and parallel designs are illustrated.

Advanced Vehicle Simulation Model: ADVISOR

In November of 1994, NREL's Center for Transportation Technologies and Systems created a simulation model for advanced vehicles called ADVISOR (ADvanced VehIcle SimulatOR) in the graphical, object-oriented programming language of Simulink/ MATLAB from the MathWorks, Inc. The model was created in support of the hybrid vehicle subcontracts with the auto industry for the Department of Energy. ADVISOR approximates the continuous behavior of a vehicle as a series of discrete steps during each of which the components are assumed to be at steady state. That is, at each time step, the effects of changing current, voltage, torque, and RPM are neglected. This allows efficiency or power loss tables, which are generated by testing a drivetrain component at a fixed torque and RPM (and current and voltage, if applicable), to be used to relate the power demands of the components at each time step. A significant advantage of using a model that is in the Simulink/MATLAB environment is the flexibility and ease of changing the model, such as replacing one control strategy or regenerative braking algorithm with another. MATLAB also allows easy plotting of results that makes detailed analysis of vehicle configurations possible.

ADVISOR is driven by the input driving profiles which can be the classic speed vs. time, such as the federal urban driving schedule (FUDS), or a speed and grade vs. time driving profile. With a given driving profile goal, ADVISOR then works its way backwards from the required vehicle and wheel speeds to the required torques and speeds of each component between the wheels and the energy source, which is either fuel from the hybrid power unit (HPU) or electricity from the batteries. Limits for each of the components are included, so the actual speed vs. time profile computed is the one that is within the limits of all components and includes all component losses and vehicle drag. Figure 1 shows the top level of the series hybrid model in ADVISOR.

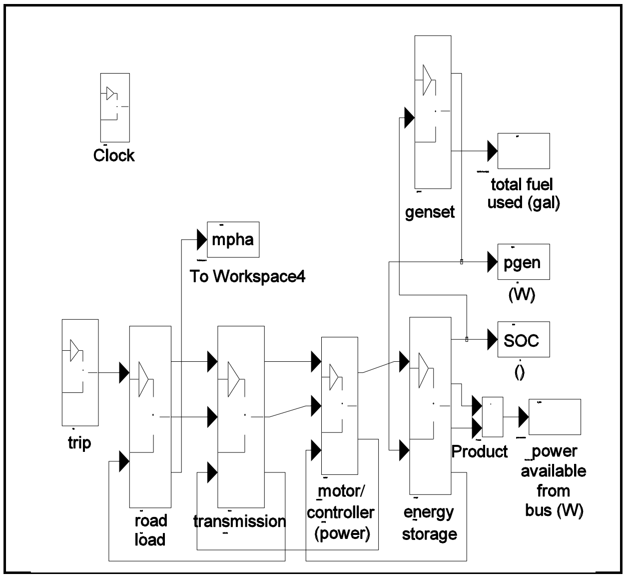


Figure 1: Top level of ADVISOR series hybrid model

Validation of the model and correlation with other vehicle simulations is extremely important to establish the credibility of a model. Through subcontracts with university teams who have built and tested successful hybrid vehicles, NREL has acquired many validated component models that include quantified uncertainties, increasing the credibility of that data. Final vehicle-level validation including detailed uncertainty analysis is scheduled to be completed in September, 1996. In the meantime, correlation with established public vehicle models has been performed, in addition to some correlations with proprietary models in the automotive industry. Based on these comparisons, ADVISOR appears to be within 2% of most models based on identical inputs. Thus, minimal uncertainty in ADVISOR's results is introduced by its algorithms; uncertainty in the input data will be the primary source of the uncertainty in ADVISOR's results. Therefore, the source of all input data for the simulations in this analysis is specified below.

Vehicles Modeled and Assumptions

Five different vehicle configurations were modeled. Both series and parallel hybrids with very low masses and highly efficient drivetrains were modeled in order to obtain PNGV-like hybrid vehicles that achieved a combined city/highway fuel economy of 80 mpg. These are referred to as "3X" vehicles because they get 3 times the fuel economy of a conventional vehicle with a combined city/highway fuel economy of 26.6 mpg (PNGV baseline, PNGV Program Plan). A third configuration was obtained by unhybridizing those vehicles to create a conventional vehicle. The fourth and fifth vehicle configurations were created by taking a conventional vehicle (at roughly 1.45X due to a diesel engine and manual transmission) and making it a parallel hybrid. Table 1 provides the key differences between the five vehicle configurations modeled and the baseline fuel economy for each vehicle configuration, while Table 2 gives the sources for the input data.

Table 1: Key Parameter Values for Vehicle Configurations Modeled

Vehicle Config.	**3X Parallel Hybrid**	**3X Series Hybrid**	**2.46X Lightwt (non hybrid)**	**1.45X Conv. (diesel)**	**1.70X Parallel Hybrid**
Mass (kg)	1000.000	1000.000	1000.000	1611.000	1611.000
Battery Cap. (kWh)	1.100	3.700	n/a	n/a	1.800
Peak HPU Power (kW)	31.000	30.000	47.000	77.000	52.000
Peak Motor Power (kW)	12.000	41.000	n/a	n/a	20.000
C_DA	0.400	0.400	0.400	0.700	0.700
$C_{\text{rolling-resistance}}$	0.008	0.008	0.008	0.011	0.011
City (mpg)	73.800	72.300	56.100	33.800	40.700
Highway (mpg)	94.300	93.600	82.100	47.000	52.800
Combined (mpg)	81.800	80.500	65.400	38.700	45.300

Scaling

Since acceleration time from 0-60 mph and gradeability at 55 mph are performance requirements for all vehicles, the HPU, which in this case is an Audi 5-cylinder turbo diesel engine, and the electric motor have both been sized so that the vehicles meet these performance targets. One major assumption in the scaling of these two components is that the torque/speed power loss maps (equivalent information as in efficiency maps) can be scaled by simply scaling the torque scale on the map. It is known that this is not the most accurate scaling method, but was used for lack of an available and justifiable scaling algorithm.

Mass

The source of the data for the mass of the conventional 1.45X conventional vehicle and the hybridized version of this vehicle came from the OTA report for a current Ford Taurus. For the 3X vehicles, the mass of 1000 kg is roughly the mass for the "Advanced Conventional" vehicle for the year 2015 from the OTA report in which almost all metal components are made of aluminum. This is certainly a significant reduction in mass from today's vehicles; this value was used to allow the efficiencies for other components and parameters to stay within today's technologies or at least the PNGV goals.

Hybrid Control Strategies

The series hybrid uses a simple "thermostat" on/off strategy to operate the HPU, with the HPU operating at a fixed torque and speed point when it is on. In this study, the HPU turns on when the batteries' state-of-charge (SOC) drops below 40% and turns off when the SOC rises above 80%.

The parallel hybrid control strategy has the effect of using the batteries for highly transient vehicle launches, unless the batteries are so low that they need to be charged. It can be defined as follows, with "high" SOC defined as 60% and "low" SOC defined as 50%:

- The HPU does not idle (it turns off when not needed).
- The motor performs regenerative braking regardless of the batteries' SOC.
- The HPU generally provides the power necessary to meet the trace and the motor generally helps if necessary, with the following exceptions:
  - when the batteries' SOC is low the HPU launches the vehicle and provides extra torque to recharge the batteries, and
  - when the batteries' SOC is high, the electric motor *only* launches the vehicle and no HPU-charging of the batteries occurs.

Table 2: Sources of Data for Simulation Inputs and Performance Requirements

Vehicle Parameter	**Values Used**	**Source of Input Data**
C_DA	0.4, 0.7 m^2	PNGV Goals, Moore, T.C
$C_{\text{rolling -resistance}}$	0.008, .011	OTA
Transmission Efficiencies: 5 spd. (parallel, conventional) / 1 spd. (series)	92% / 98%	Automotive Engineering, 1996
Heat Engine (HPU)	Scaled 85 kW TDI Diesel	Stock, D., 1990
Motor/Controller	Scaled 75 kW AC Induction	Lesster, L., 1993
Energy Storage: Batteries	Horizon 12N85	Electrosource
0-60 mph time	12.0 seconds	PNGV Goals
Gradeability at 55 mph	6.5% indefinitely	More stringent than PNGV goal, which is 6.5% for 20 minutes

Fuel Economy Calculation

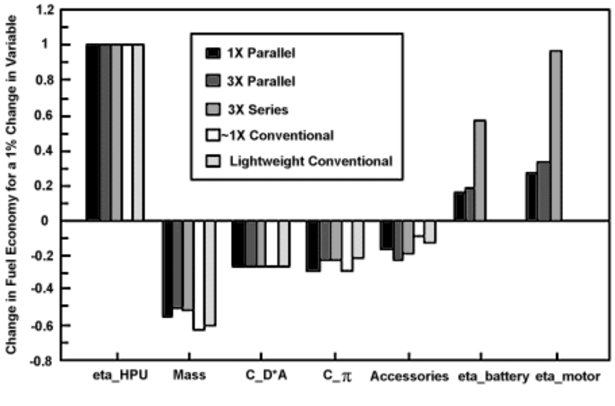
To account for changes in the battery pack's SOC during a test cycle, a simplified version of the proposed SAE Hybrid Vehicle Test Procedure is being used. To come up with the city fuel economy, two FUDS are run back-to-back from a high SOC and then from a low SOC, causing a decrease and an increase in battery SOC, respectively. A simple linear interpolation is then used to predict the fuel economy estimate for the vehicle if the batteries had no net change in SOC. This ensures a fair comparison between conventional vehicles and hybrid vehicles by accounting for any electrical energy surplus or deficit in the hybrid vehicle's battery pack. Without such accounting for the change in SOC of the battery pack, the hybrid might appear to have an extremely high fuel economy due to electric energy being used in place of fuel energy.

Sensitivity of Fuel Economy to Key Vehicle Parameters

A sensitivity analysis of the key parameters for a simulated vehicle illustrates how sensitive the output (fuel economy in this case) is to changes in the input parameters. This allows a side-by-side comparison of the input parameters in order to focus on technology areas that are important to the final fuel economy. In addition to the relative comparisons possible, it also provides numbers from which fuel economy changes due to input parameter changes can be easily calculated. For each of the five base case vehicles each of the key parameters was adjusted up by 5% and down by 5%, resulting in two points from which the slope was calculated. Note that these coefficients are useful beyond the 10% spread over which they were calculated, but the absolute value of the results they predict shouldn't be trusted beyond about +/-10%.

For the five vehicles modeled a sensitivity analysis was performed, and the results are shown in the bar chart of Figure 2. Refer to Table 1 for the baseline parameters for each of the five vehicles listed in the figure. Notice that the sensitivity coefficient for the HPU for all five vehicles is 1.0. This means that for a 1% increase in engine efficiency, there will be a 1% increase in fuel economy. Since the engine is the prime energy converter onboard a hybrid or conventional vehicle, this is not surprising, but is still important to keep in mind. Because of this large sensitivity to HPU efficiency, there is significant industry and government effort placed into research on gas turbines, advanced diesels, stirling engines, and fuel cells.

Figure 2: Sensitivity of Fuel Economy to Key Vehicle Parameters



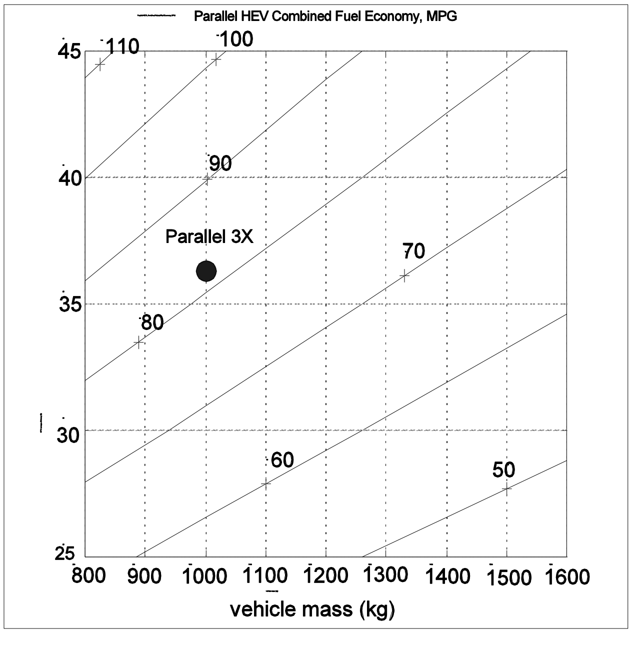
The results in Figure 2 show that the sensitivity coefficients for the battery efficiency (eta_battery) and the motor efficiency (eta_motor) for the 3X series vehicle are roughly 3 times those of the parallel vehicles. The reason for this is that since all of the power to the wheels from a series hybrid comes from the electric motor, higher power and hence higher power losses are experienced in the motor. Also, for series hybrids more energy is passed through the batteries than in parallel vehicles, incurring larger losses in the batteries. In terms of technology risk, this indicates that series HEVs are more affected by efficiency improvements in the motor and batteries than parallel hybrids, and are at a greater risk of not meeting fuel economy goals if anticipated improvements do not come through.

The four parameters below the axis are parameters that decrease fuel economy when they are increased. The goal is to keep these parameters as low as possible. Take the example of minimizing accessory loads for a parallel 3X vehicle: for every 1% decrease in accessory load, there is a 0.24% increase in fuel economy. With a baseline accessory load of 800W, a 10% reduction (80 W) results in a 2.4% increase in fuel economy. These results allow a fuel economy tradeoff to be quantified for additional features on a car such as daytime-running lights.

Mapping out the HEV Design Space Through Parametric Studies

Figure 3 shows fuel economy contours computed with ADVISOR as a function of average HPU efficiency and vehicle mass for a parallel hybrid vehicle with the aerodynamic drag and rolling resistance of the 3X parallel vehicle in Table 1. Note that the 80 mpg fuel economy contour is the one that defines the fuel economy goal for the PNGV.

Figure 3: Fuel Economy as a Function of HPU Efficiency and Vehicle Mass for a Parallel Hybrid



Two vehicle masses of interest Figure 3 are at 1000 kg and just above 1600 kg, the two masses used in the construction of the 5 vehicle configurations. It is clear from this graph that weight savings coupled with drag reduction is still not enough to get to 80 mpg (3X) from today's conventional spark ignition engine which has an average HPU efficiency of ~25%. The mass would have to be more than cut in half, which is not feasible in the near future. Likewise, this graph shows it is difficult to achieve 3X with only HPU efficiency improvements, hybridization, and vehicle drag reduction. Extrapolating from this chart, we infer that a 3X vehicle at 1600 kg would require an average HPU efficiency of 47%, well beyond the average efficiency range of diesels this size.

Effect of Hybridization

To isolate the effects of hybridization, that is, replacing a conventional vehicle's propulsion system with a hybrid system, the 3X hybrids were unhybridized and the 1.45X conventional was hybridized in the initial design of the five vehicle configurations. Referring to the combined fuel economy results in Table 1, the lightweight conventional gets 65.4 mpg while the 3X series and parallel hybrids get 80.5 and 81.8 mpg, respectively. Thus, the effect of hybridizing a lightweight conventional that gets 65.4 mpg is roughly a 24% improvement, assuming that the hybridization could be done for the same total vehicle mass. For the 38.7 mpg conventional vehicle, hybridization adds a 17% boost in fuel economy in this particular case. It should be noted that these vehicles' hybrid systems are not optimized. The values of hybridization estimated here should not be taken as upper limits, but rather as representative values.

Another aspect of hybridization that can be examined from the results obtained on the two 3X hybrids is the difference between series hybrids and parallel hybrids. For these two unoptimized hybrids, the fuel economy came out to 81.8 mpg for the parallel and 80.5 mpg for the series. This means that based on the assumptions made for these hybrids, including the assumption that the mass would be the same, both hybrid configurations come out with almost exactly the same fuel economy.

A reasonable argument could be made that the battery pack for a series hybrid would have to be more powerful and heavier than for the parallel hybrid. If a mass of 1100 kg were used for the series hybrid rather than the 1000 kg initially assumed, a combined fuel economy of roughly 76.5 mpg results. Let us consider two independent technology improvement paths to get back to 80 mpg. Figure 4 is the 2D design space of fuel economy as a function of driveline efficiency (motor, motor controller, and transmission) and accessory load for the 3X series hybrid with a mass of 1100 kg.

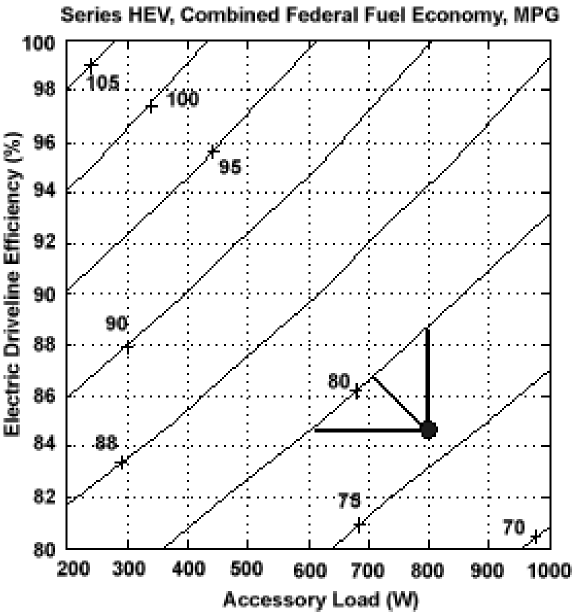


Figure 4: Fuel Economy as a Function of Driveline Efficiency and Accessory Load for 1100 kg Series Hybrid

As indicated by the arrows going from the dot representing the 1100 kg baseline vehicle, with an 800 W accessory load and an 84.5% efficient electric drivetrain, to the 80 mpg contour, there are many possible paths to get back to 80 mpg for this vehicle: reduce accessories by 200 W, improve driveline efficiency by 4%, or some combination of the two. Given that the series hybrid considered here has a highly efficient, developmental AC induction motor feeding into a 98% efficient single-gear transmission, the opportunities for driveline efficiency improvements are limited. The prudent designer may be more inclined to try to reduce auxiliary loads.

Conclusions

An advanced vehicle simulator called ADVISOR was developed at NREL for the Department of Energy to allow system-level analysis and trade-off studies of advanced vehicles. Five vehicle configurations were modeled and sensitivity coefficients for key parameters of these vehicles were calculated. The fuel economy design space for a parallel and a series hybrid were examined and possible scenarios to reach 80 mpg were discussed. For the vehicles modeled, the fuel economy benefit due to hybridization was found to be between 17-24%. The 3X series and parallel vehicles were found to get the same fuel economy at the same mass, but if the series vehicle were 100 kg heavier, it would be a challenge to make it reach 80 mpg.

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