# Optimization of a Hybrid Electric Bus

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## Introduction

Fuel-efficient and environmentally friendly ground vehicles, with range and performance capabilities surpassing those of conventional vehicles, require a careful balance among competing goals for fuel economy, performance and emissions. Hybrid electric vehicles (HEVs) require complex optimizations to account for the intricate interactions among their components and their effects on the outcome of the performance of the vehicle. Since HEV models and interactions are so complex, it can be difficult to properly define an optimization problem statement that invokes the desired final design. The way the optimization problem statement is defined greatly affects the performance of the optimal HEV design, as well as the implications of the design.

The design landscapes of HEVs add to the complexity of using optimization effectively in their design. These landscapes are known to be highly non-linear, non-continuous, and to have a large number of local optima (multi-modal) [1, 2], making the search for the optimal design even that much more difficult.

This paper demonstrates a strategy for optimizing HEVs that accommodates the complexity of the HEV problem statement, interactions among the HEV components, and the design landscape. It summarizes the work of optimizing a hybrid electric bus [3], and provides the final strategy found for making the optimization search more efficient in finding optimal designs that are expected to perform well in the field. An integrated simulation and design optimization framework is presented to find the best overall combination of engine size, battery pack, electric motor and generator for minimum fuel consumption under specified performance criteria.

## Modeling of a Hybrid Electric Bus

ADVISOR (advanced vehicle simulator) was used as the modeling and simulation tool for the hybrid electric bus studied. ADVISOR utilizes a combined forward/backward simulation approach to evaluate a vehicle's performance [4]. It is frequently used in conjunction with Matlab to simulate HEVs.

The hybrid electric bus considered here had a series configuration (as shown in Figure 1), with the baseline components listed in Table 1 [5]. The optimization study focuses on the sizing of the generator, electric motor, engine, and battery. Utilizing a scaling method, the best combination of sizes for these devices to meet the needs of the specific application was found.

*Table 1. Baseline components of the series hybrid bus for optimization.*

| Component | Characteristics |
|---|---|
| Engine | Detroit Diesel Corp. Series 50 8.5 (205kW) Diesel Engine |
| Motor | UQM 150 kW motor/controller |
| Generator | UQM 150 kW generator |
| Battery | NIMH 90Ah Ovonic |
| Wheel and Axle | ACCURIDE, wheel radius = 0.45 |
| Transmission | Single gear, with overall ratio (8.074:1). |
| Accessory | Mechanical and electrical power scaled of ~ 21.4 kW (29 hp) with A/C |

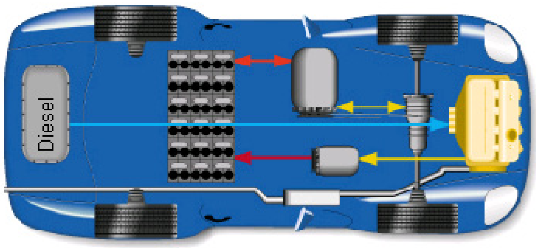


*Figure 1. Powertrain configuration of the HEV bus (as it appears in ADVISOR).*

A thermostat control strategy was used for this hybrid bus. This type of control strategy allows the user to specify a lower/upper limit for the state of charge (SOC) of the battery, below/above which the engine turns on/off and the generator charges/discharges the battery. It should be noted that for a thermostat control strategy, when the engine is on, it is run at a constant speed (the speed at which the engine operates most efficiently). For the optimization study, the lower limit and upper limit on the state of charge for this thermostat control strategy were defined as:

Lower Limit on SOC: 0.52
Upper Limit on SOC: 0.68

These values are consistent with the expected operation of the bus.

## Optimization Problem Statement

The objective of the optimization was to size the various components in a manner that minimized fuel consumption while meeting performance characteristics for a given drive cycle (the UDDS Drive Cycle). HEEDS was used as the optimization tool and ADVISOR as the simulation tool. HEEDS' proprietary search algorithm, SHERPA, was employed in this study due to the difficult design landscape known to exist for HEVs. SHERPA (a hybrid, adaptive search algorithm) has been shown to work well on a wide variety of problems, including multi-modal, noisy, discontinuous problems (representative of an HEV's design landscape). Other local methods and monolithic algorithms were shown to be inferior on these types of problems [2,6].

Through previous studies, it was discovered that the optimization problem statement used has a very strong influence on the resulting optimal design found. The following lessons were learned from these previous studies:

- If a single run cycle is performed, the optimal design found may be an entirely electric vehicle (EV), highly dependent upon the initial state of charge (SOC) specified for the run.
- If no constraint is imposed upon the minimum SOC during the run, the optimal design may have an engine too small to handle the driving demand and a small generator unable to adequately charge the battery, resulting in a design that has good fuel economy but a very depleted battery (much less than the desired minimum SOC of 0.52).
- Using a single initial SOC greatly influences the optimal design. It is better practice to use multiple load cases for each design, where each load case corresponds to a different initial SOC. The fuel economy used to judge the performance of a design is then the average fuel economy of all the load cases.

In the current study, each design during the optimization had multiple run cycles performed for multiple load cases (with each load case having a different initial SOC). The goal of the optimization was to maximize the average fuel economy over all the run cycles. In addition to performance constraints on acceleration and drivability of the bus, a constraint on the minimum SOC attained during the runs was also imposed. The optimization problem statement was therefore:

**Maximize:**

*composite fuel economy* (average miles per gallon of gasoline from all initial SOC loadcases)

**Subject to:**

*missed_trace (mph)* ≤ 5.0 (how close the bus was to meeting the drive demands of the cycle)

*minimum SOC* ≥ 0.5175 (lowest state of charge over all initial SOC loadcases)

$t_{60}$ ≤ 42.0 s (time to accelerate to 60 mph from start)

$t_{30}$ ≤ 10.0 s (time to accelerate to 30 mph from start)

**By varying:**

*Number of battery modules* = {15,16, .. ,50}
0.3 ≤ *Battery Capacitance Scale* ≤ 1.5
0.5 ≤ *Engine Speed Scale* ≤ 1.5
0.5 ≤ *Engine Torque Scale* ≤ 1.5
0.5 ≤ *Generator Speed Scale* ≤ 1.5
0.5 ≤ *Generator Torque Scale* ≤ 1.5
0.5 ≤ *Motor Speed Scale* ≤ 3.0
0.5 ≤ *Motor Torque Scale* ≤ 3.0

**With:**

*Upper SOC Limit* = 0.68
*Lower SOC Limit* = 0.52
*Initial SOC* = {0.52, 0.60, and 0.69}
(multiple initial SOC loadcases)

## Baseline Design

A baseline conventional bus was used to gauge the performance of the optimization. This conventional bus (non-hybrid) had the same applicable design characteristics as the hybrid of Table 1 (engine, wheel and axle, transmission, and accessories). Since the hybrid bus to be designed was to replace this conventional bus, it is a logical choice as the baseline for comparison.

The conventional bus had the following performance characteristics:

*fuel economy:* 4.7 mpgge (miles/gallon gasoline equivalent) *missed_trace:* < 5 mph

$t_{60}$ = 68.6 s

$t_{30}$ = 13.3 s

Note that the conventional bus was feasible in terms of meeting the drive demands of the cycle, but infeasible in its acceleration times.

## Optimal Design

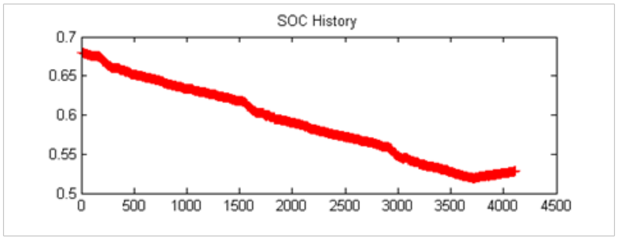
The optimal design found during the optimization study had the design characteristics of Table 2. Note that the battery capacitance and battery module numbers were increased over the baseline battery specifications of Table 1 (*ESS CAP = 1.0, ESS MOD NUM = 20)*. The engine speed was increased, while the engine torque decreased from that used in the conventional bus. Likewise the generator speed was increased while the generator torque was decreased over that of the baseline generator specifications of Table 1 (*GC SPEED = 1.0, GC TORQUE=1.0).* The motor, meanwhile, had its speed reduced to the minimum allowable value and torque increased to the maximum allowable value.

*Table 2. Resulting optimal design for the series hybrid bus.*

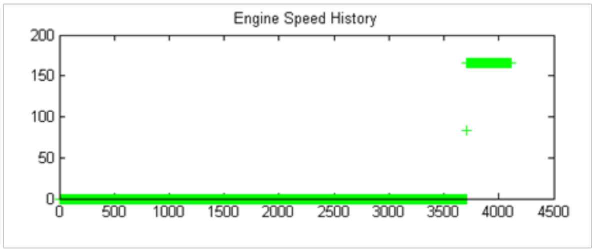
| **Optimal Variable Values** | | **Responses** | |
|---|---|---|---|
| ***ESS CAP*** | 1.5 | ***Average Fuel Econ. (mppge)*** | 13.23 |
| ***ESS MOD NUM*** | 50 | ***Individual Analysis Fuel Econ. (mppge)*** | 30.94, 5.53, 3.21 |
| ***FC SPEED*** | 1.15 | ***Delta Trace (mph)*** | 2.12, 2.12, 2.12 |
| ***FC TORQUE*** | 0.65 | ***Average SOC*** | 0.591,0.545, 0.537 |
| ***GC SPEED*** | 1.32 | ***Acceleration 0-60*** | 17.64 |
| ***GC TORQUE*** | 0.89 | ***Acceleration 0-30*** | 6.61 |
| ***MC SPEED*** | 0.5 | | |
| ***MC TORQUE*** | 3.0 | | |

The average fuel economy of the optimal design was 13.23 mppge (a > 250% increase over the conventional bus). The individual analysis fuel economy numbers explain this huge improvement in performance.

The 0.68 initial SOC analysis had a fuel economy of 30.94 mppge. Figure 2 shows the characteristics of this analysis. From this figure it is evident that even with the multiple run cycles this optimal design runs primarily as an EV for most of the analysis.



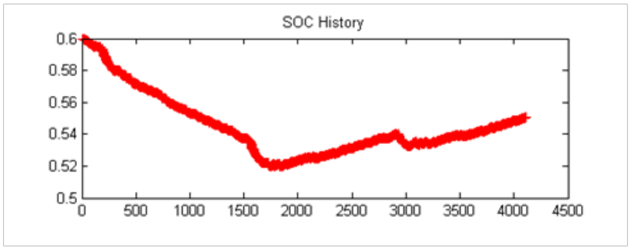
*(a) SOC history plot*



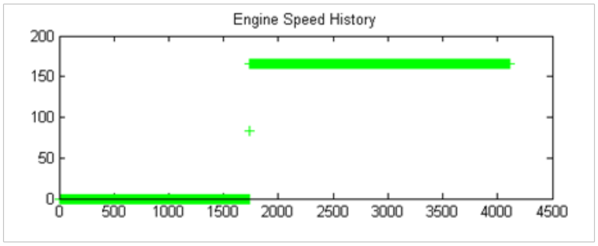
*(b) Engine speed history plot*

*Figure 2. Optimal design characteristics if initial SOC is 0.68 over 3 run cycles of the UDDS.*

The second analysis with a 0.60 initial SOC does not operate in this manner (see Figure 3) and has a fuel economy of 5.53 mppge.



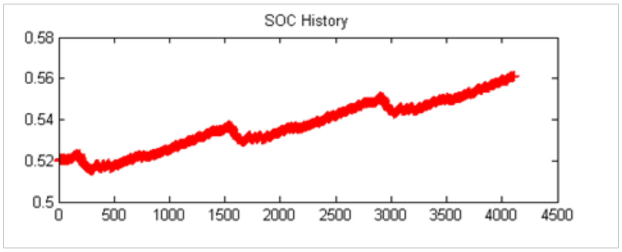
*(a) SOC history plot*



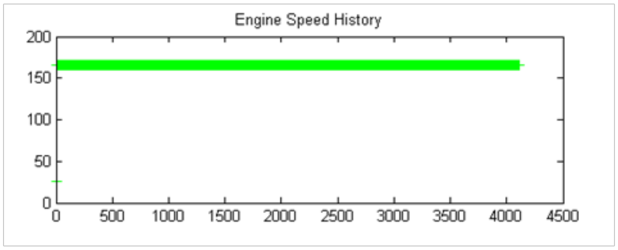
*(b) Engine speed history plot*

*Figure 3. Optimal design characteristics if initial SOC is 0.60 over 3 run cycles of the UDDS.*

The third analysis with a 0.52 initial SOC has the lowest fuel economy at 3.21 mppge, since it has to run the engine the most to recharge the already depleted batteries at the beginning of the run cycle (see Figure 4).



*(a) SOC history plot.*



*(b) Engine speed history plot.*

*Figure 4. Optimal design characteristics if initial SOC is 0.52 over 3 run cycles of the UDDS.*

So it is apparent that the initial SOC of the bus when it begins its routes will play a role on the fuel economy achieved. Over time, though, on average the optimized HEV bus will achieve a significantly higher fuel economy than the conventional bus, while meeting the performance constraints, which the conventional bus did not do.

## Conclusion

HEEDS was successful in optimizing a series hybrid bus that substantially outperformed the conventional version of the bus (> 250% better average fuel economy), using ADVISOR as a simulation tool. The optimization was performed utilizing key conclusions from previous optimization studies: multiple run cycles need to be performed, multiple initial SOC's need to be utilized to evaluate a given design, and a minimum SOC constraint must be used to avoid designs that are not able to recharge the batteries.

## References

1. M. Montazeri-Gh, A. Poursamad, B. Ghalichi, "Application of genetic algorithm for optimization of control strategy in parallel hybrid electric vehicles," *Journal of the Franklin Institute*, pp. 420-435, 2006.
2. W. Gao, S. Porandla, "Design Optimization of a Parallel Hybrid Electric Powertrain," *Proceedings of the IEEE Vehicle Power and Propulsion Conference*, Chicago, 2005.
3. N. Chase, K. Sinha, R.C. Averill, *Optimization Strategies for Hybrid Electric Vehicles,* 2009.
4. ADVISOR User's Manual, 2004.
5. N. Chase, *Thesis: Advanced Optimization Strategies for Automotive Applications*, Michigan State University, 2009.
6. N. Chase, M.Rademacher, E.Goodman, R.Averill, R.Sidhu, *A Benchmark Study of Optimization Search Algorithms,* Red Cedar Technology, BMK-3022, 2008.