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Dynamic Programming Applied to Investigate Energy Management Strategies for a Plug-in HEV

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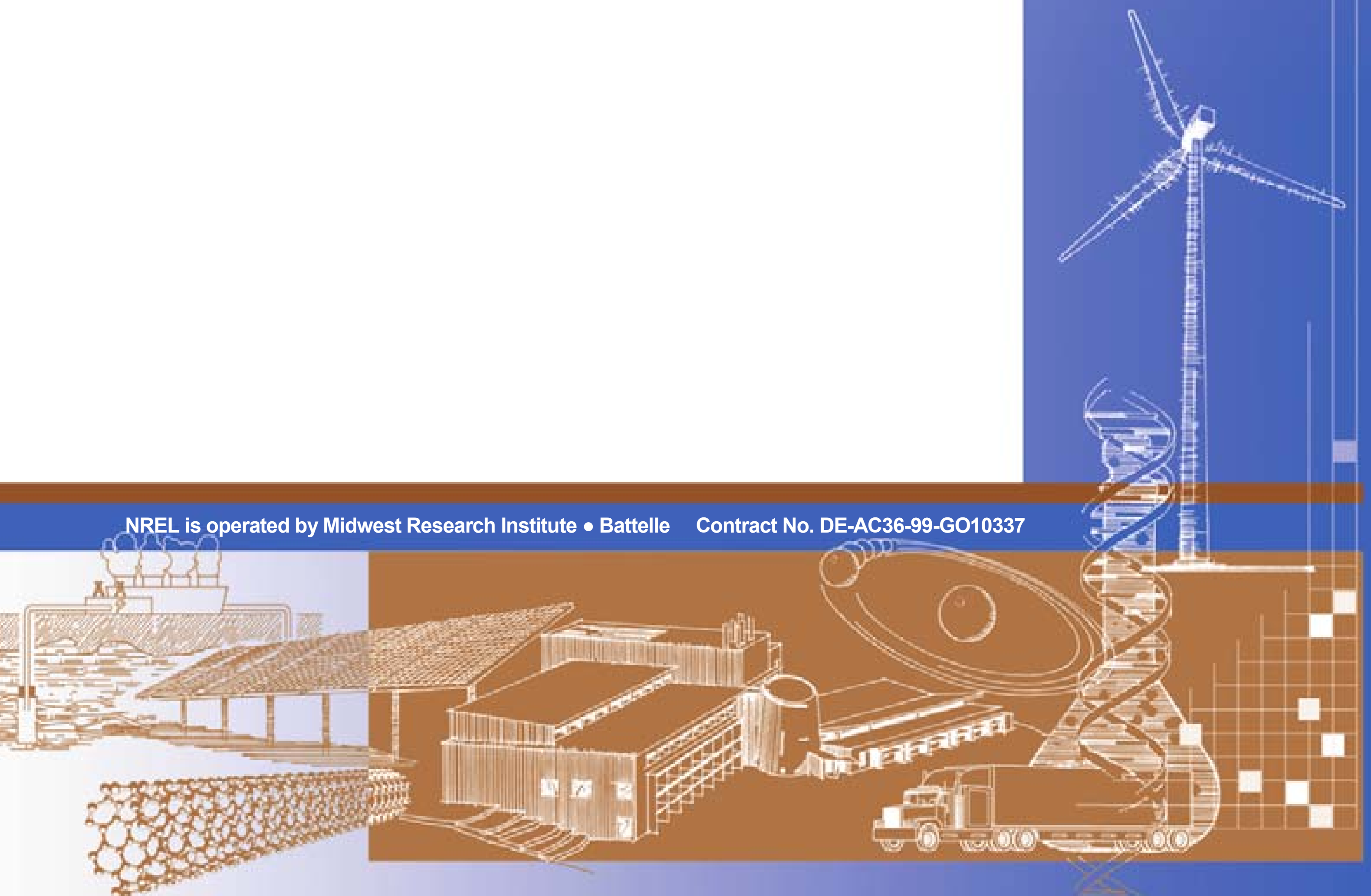

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Dynamic Programming Applied to Investigate Energy Management Strategies for a Plug-In HEV[1]

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Abstract

Plug-in hybrid electric vehicles (PHEVs) are an advanced dual-fuel powertrain technology that combine features of the battery electric vehicle (BEV) and hybrid electric vehicle (HEV). One of the fuels of the PHEV is electricity which is supplemented by another fuel (typically gasoline). The gasoline consumption for a PHEV is distance dependent based on the vehicle control strategy. In this paper, we explore two basic control concepts applied to a PHEV: an "electric vehicle centric" control strategy and an "engine-motor" blended control strategy. A near optimal control solution is derived using the dynamic programming optimization algorithm. Based on comparison with the dynamic programming results, we show that for urban driving, a PHEV should typically operate closer to an "electric vehicle centric" control strategy to provide consistently high fuel savings. We also show that PHEVs with smaller motors and lower power-to-energy ratio batteries can save nearly the same amount of fuel as a full-size PHEV—but perhaps at a reduced cost.

Keywords: Plug-In Hybrid, Hybrid Strategy, Energy Efficiency, Modeling, Dynamic Programming

1 Introduction

1.1 Plug-In Hybrid Electric Vehicles

Plug-in hybrid electric vehicles (PHEVs) are a dual-fuel technology capable of transforming the transportation energy infrastructure away from non-renewable, high-carbon fuels to more environmentally responsible options. One of the PHEV fuels is electricity. The other fuel could be one of any number of options, although gasoline is considered here.

PHEVs can deliver performance equivalent with today's modern vehicles. Furthermore, compared with other technology options, the PHEV does not suffer from some of the infrastructure issues (e.g., fuel cell vehicles) nor the limited range issues (e.g., battery electric vehicles) exhibited by other technologies. These positive benefits are the result of both efficient delivery of fuel-energy from the tank to the wheels and, more importantly, a transition from conventional transportation fuels to electricity. This is possible because PHEVs exhibit aspects of both battery electric vehicles (BEVs) and hybrid-electric vehicles (HEVs):

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- A large energy storage unit capable of being recharged from the electrical utility grid and supplying net motive energy over a significant distance
- A hybrid powertrain typically using an internal combustion engine with an electrical motor

By blending aspects of the BEV with conventional HEVs, one can gain many of the advantages of a BEV while eliminating several disadvantages. Because fewer batteries are needed than a full BEV, the PHEV comes with a reduced cost penalty versus a BEV of equivalent performance. Furthermore, the PHEV has no range penalty and charging times are much shorter than an equivalent BEV. In contrast to an equivalent HEV, fuel consumption is further reduced since fuel energy is supplied from both electricity and liquid fuel as opposed to just liquid fuel as is the case for conventional HEVs.

PHEVs work well for vehicles that operate where relatively short trips comprise the bulk of distance traveled. By recharging between these short trips, a large portion of the motive energy can come from the electrical grid as opposed to gasoline or other fossil fuels. The transition from today's petroleum-based transportation fuels to electricity opens up many opportunities. By recharging the vehicle's batteries overnight, electrical utilities can increase their operating efficiency. Furthermore, due to the difference between peak capacity and base-load capacity, power utilities will typically have enough excess capacity at night to recharge a large number of vehicles before having to add new capacity. If done correctly, this can lead to reductions in carbon dioxide (CO_2) and other greenhouse gas emissions. Furthermore, if effort is made to transform the power plants within the national electrical grid to use more renewable sources of energy, the benefits of renewable energy can be brought to the transportation sector through PHEVs.

However, PHEVs do have some challenges for commercialization. Chief among these are cost which is largely connected with batteries and battery life, in addition to the added cost of PHEV power electronics and powertrain components.

In this paper, we will explore two separate PHEV architectures. Both vehicles yield equivalent performance and have the same electrical capacity in the vehicle energy storage system. The first, referred to as the full-size PHEV, contains a high-power motor and energy storage unit with smaller internal combustion engine (ICE). The second vehicle, referred to as the half-size PHEV, uses a lower power motor with lower power energy storage and larger ICE. The second vehicle represents a lower-cost PHEV solution because it deemphasizes the (expensive) electric powertrain components such as high-powered batteries and emphasizes ICE technology.

In addition to the vehicle architectures, we also discuss two different PHEV energy management strategies: an "electric vehicle centric" approach and a blended-control approach. In the "electric vehicle centric" approach, the motor and batteries attempt to meet all traction demand electrically, with the engine only helping when the motor is not powerful enough. This strategy uses electricity whenever possible. The blended control approach attempts to spread the electrical consumption over a larger distance by blending engine power with motor usage at times when the system is more efficient.

In order to compare these control paradigms, the dynamic programming algorithm, which can determine the near-optimal solution of any control problem, is used.

1.2 The Dynamic Programming Method

Dynamic programming is a numerical technique that can be applied to any problem that requires decisions to be made in stages with the objective of finding a minimal penalty decision pathway [1]. "Penalty" used in this sense refers to a quantitative measure of the undesirable outcomes of a decision. Dynamic programming combines knowledge of the immediate penalty of the decision at hand with knowledge of future penalties that arise as a result of the immediate decision. This algorithm has been applied with success to HEVs in the past [2], though the authors are unaware of any application to PHEVs to date.

Dynamic programming requires the definition of a discrete time dynamic system (DTDS) and a penalty function. Because the dynamic programming algorithm is quite computationally intensive, a fast computational model is desired for the DTDS. In the context of this paper, the DTDS is a vehicle model which calculates the change in state (battery state-of-charge) resulting from a given control setting (the engine shaft out power) over a time-step along a duty cycle. The duty cycle, the vehicle's commanded speed versus time, is treated as deterministic for this study. The algorithm proceeds from the end of a duty cycle to the beginning, calculating the penalty of possible control settings at each time step. Because knowledge of the duty cycle is required beforehand, the dynamic programming algorithm cannot be implemented in actual control systems in real life. However, outputs from the dynamic programming algorithm can be used to formulate and tune actual controllers.

The penalty function used in this study attributes a penalty for using fuel, not meeting the specified duty cycle speed-time trace, and for not holding end state-of-charge at a reasonable level.

The dynamic programming algorithm as used in this study only explores a subset of the entire design space. Because of this, the control cannot be said to be "optimal," only "near-optimal".

There are two main reasons to employ the dynamic programming method in this study:

- To compare PHEV architectures under "near-optimal control"
- To gain insights into what the "optimal" control is for a PHEV under various circumstances.

By comparing all PHEV architectures under an "optimal control," control itself is eliminated as a design variable from the problem.

2 Analysis Overview

This study compares the energy implications for two PHEV architectures over multiple urban duty cycles (driving patterns) and multiple distances using a "near-optimal" control strategy derived via the dynamic programming algorithm. Both vehicles contain enough electrical energy to drive approximately 32 km (5.5 kWh usable capacity). The selection of this capacity and specific sizes is based on a cost benefit analysis of PHEVs conducted by Simpson [3]. Both vehicles in this study use a parallel hybrid design where the engine and/or motor can contribute to tractive effort at any time. Gasoline is assumed for the liquid fuel in this study. However, it is important to note that PHEVs could use other fuels such as diesel, ethanol (E85), or even hydrogen if the ICE is properly designed to handle the given fuel.

2.1 Vehicle Platform, Performance, and Assumptions

The vehicle platform used for this study is a mid-size sedan with performance requirements specified so as to be competitive in the North American marketplace. The specific requirements are given below in Table 1.

Table 1: Mid-Size Sedan Performance Requirements and Platform Assumptions

Attribute	Value
Top Speed *top speed to be maintained*	177 km/hr (110 mph)
Full Acceleration *time from 0 km/hr to 96.6 km/hr (60 mph)*	8.0 seconds
Passing Acceleration *time from 64.4 km/hr (40 mph) to 96.6 mph (60 mph)*	5.3 seconds
Hill Climbing *grade (percent rise over road-surface run) to climb with engine at 66% of rated power*	6.5% grade @ 88.5 km/hr (55 mph)

Range *maximum distance traveled starting fully fueled*	643.7 km (400 miles)
Glider Mass *the mass of the vehicle minus the powertrain*	905 kg
Cargo Mass *the mass of cargo carried while meeting performance constraints*	136 kg
Accessory Loads *the accessory loads assumed for the PHEV*	0.7 kW electric average 4.0 kW electric peak
Transmission Efficiency *efficiency of the mechanical gearing between motor/engine and wheels*	85%
Electrical Generation Efficiency for Accessories *efficiency of generating the power to electrical accessories*	85%

These requirements imply minimum component sizes. The peak accessory loads are assumed to be engaged for purposes of calculating the hill climbing and top speed power requirements. All other calculations (including fuel consumption calculations) assume average accessory loads. The resulting component requirements for a conventional vehicle and two PHEVs are given in Table 2.

Table 2: Component Sizes and Weights Used in Study

Component	**Conventional Vehicle**	**Full-Size PHEV**	**Half-Size PHEV**
Spark Ignited Internal Combustion Engine	121.7 kW peak 238.6 kg	80.1 kW peak 171.3 kg	99.2 kW peak 202.2 kg
Electric Motor and Inverter	NA	44.1 kW peak 45.1 kg	21.4 kW peak 33.0 kg
Battery Pack	NA	5.50 kWh usable 47.2 kW peak 11.8 kWh full capacity 94.4 kg	5.57 kWh usable 23.9 kW 11.9 kWh full capacity 79.6 kg
Gasoline and Tank	509 kWh 49.1 kg	396 kWh 38.2 kg	416.7 kWh 40.2 kg
Transmission	167.9 kg	176.0 kg	176.8 kg
Support Structure	68.3 kg	78.8 kg	79.8 kg
Glider Mass	905.0 kg	905.0 kg	905.0 kg
Cargo Mass	136.0 kg	136.0 kg	136.0 kg
Total Vehicle Mass	1428.9 kg	1508.8 kg	1516.6 kg
Tested Mass	1564.9 kg	1644.8 kg	1652.6 kg
Degree of Hybridization	0%	35.51%	17.75%

There are some subtleties in Table 2 that should be pointed out. First, note that advanced battery specifications are assumed. Next, the type of battery used in the full size PHEV is different from that used in the half-size PHEV. If one examines both batteries, you will quickly see that the usable capacity of both packs is nearly the same (the slight difference is due to the difference in weight and requirement for both vehicles to drive the same range). However, the weights of both packs and the pack powers are different. This arises from a difference in battery pack power-to-energy ratio. The energy density of batteries differs by power to energy ratio. Low power-to-energy ratio batteries also tend to be slightly less expensive as a technology. For more detail on how cost and weight of each component interact with vehicle requirements, see the paper by Simpson [3].

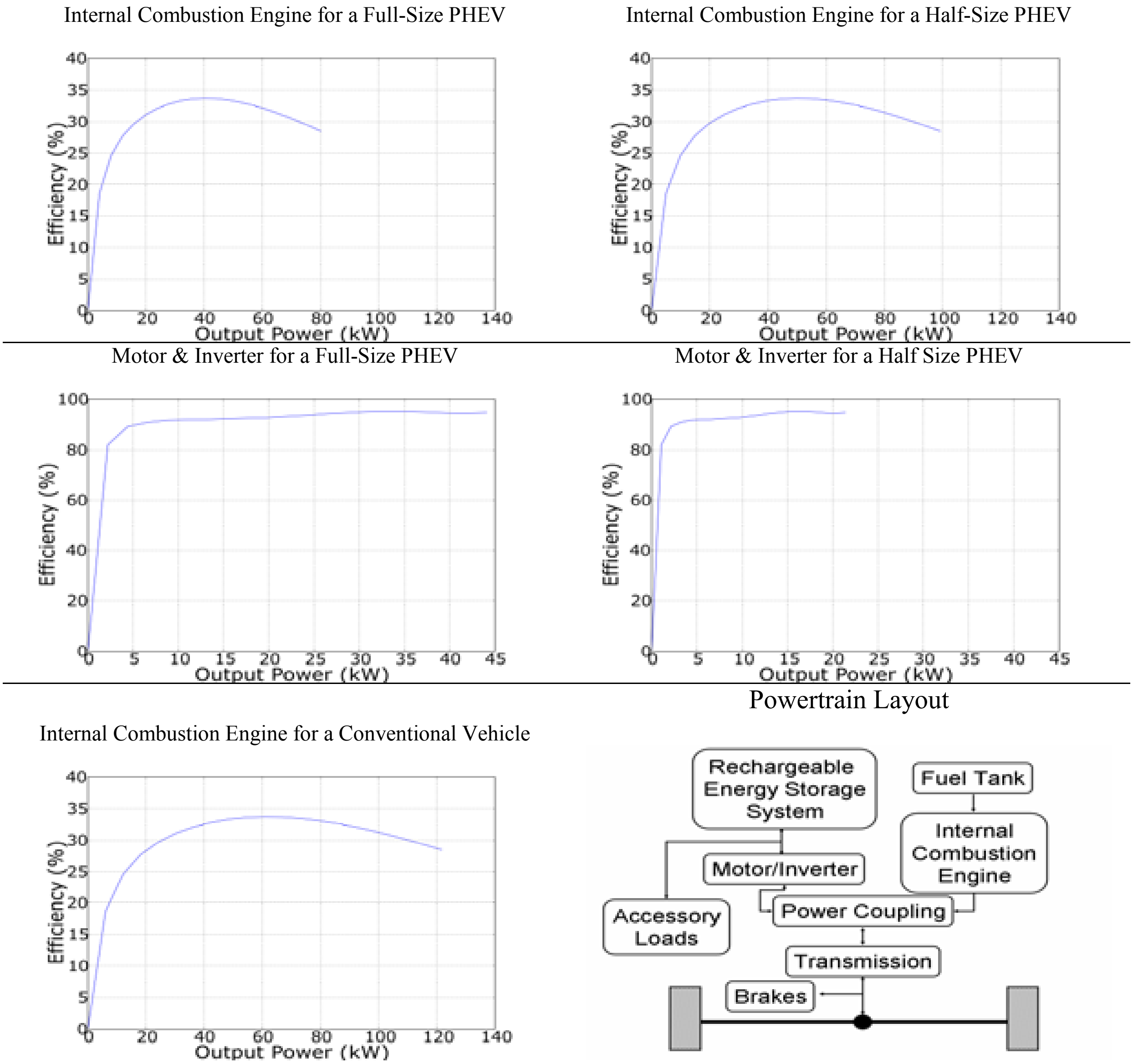
The degree of hybridization of both PHEVs appears in Table 2. This percentage is the ratio of the motor power to the engine plus motor power. The degree of hybridization of the “half-size” PHEV is half that of the full-size PHEV, hence the name.

2.2 Vehicle Model

The vehicle model is used as the discrete time dynamic system (DTDS) by the dynamic programming algorithm. The model takes in a single control setting for each time step—the desired ICE shaft-out power for that time step. Based on the ICE shaft output power, the motor will either accept or transmit power so as to satisfy the tractive effort and accessory loads required for the given time step. The model also contains state information. The only state variable is the battery state-of-charge at the beginning of a time step. Based on the tractive effort required during the time step (defined by the duty cycle) and the control setting for ICE power, the battery state-of-charge will change.

Because the dynamic programming method is computationally expensive (requiring many model evaluations), the vehicle model used in this study has been constructed to contain only the minimum required detail so as to be quick. For example, components in the powertrain use models of power and efficiency as opposed to torque, speed, and efficiency.

A schematic of the powertrain layout and a listing of component efficiencies by output power are given for the ICE and motor/inverter components of the full-size and half-size vehicles in Figure 1.



Internal Combustion Engine for a Full-Size PHEV

Internal Combustion Engine for a Half-Size PHEV

Motor & Inverter for a Full-Size PHEV

Motor & Inverter for a Half Size PHEV

Internal Combustion Engine for a Conventional Vehicle

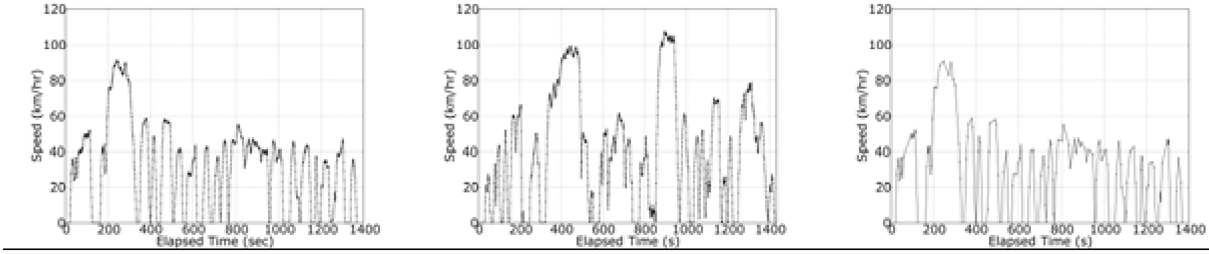
Powertrain Layout

Figure 1: Component Efficiency Maps by Shaft Output Power and Powertrain Layout

The model is written in an open-source object oriented programming language called Python and uses the following open source modules: Numeric Python, Scientific Python, and Matplotlib [4, 5, 6]. The model does not at this time include details related to engine start-stop (i.e., durability constraints, vibration, emissions considerations).

2.2 Duty Cycles Examined

The scope of this study is limited to urban driving. Two cycles, the Urban Dynamometer Driving Schedule (UDDS) and the Los Angeles 1992 (LA92) cycle are used to represent aggressive and passive urban driving. A simplification of the UDDS cycle has been substituted for the real UDDS in the interest of simulation time. The simplified UDDS cycle approximates the full UDDS using fewer time-steps, which aids in speeding up the dynamic programming algorithm. This is a great time saver during dynamic programming runs using higher design space resolution. Graphs of the time-speed traces appear below in Figure 2.



Urban Dynamometer Driving Schedule (UDDS)

Los Angeles 1992 (LA92)

Urban Dynamometer Driving Schedule Approximation (UDDS-a)

Close-up of UDDS Cycle

Close-up of UDDS-a Cycle

Figure 2: Drive Cycles Used in this Study

3 Analysis Results

The gasoline fuel consumption predicted by the models over the LA92 and UDDS-a cycles is given below in Table 3. A lower heating value of 32 MJ/liter of gasoline is assumed. The values given for fuel economy for this mid-size sedan are reasonable for the North American market. The charge sustaining fuel consumption numbers for the PHEVs represent a best case scenario for hybrid fuel savings. Fuel savings from the PHEV relative to the conventional vehicle arise from three main sources: regenerative braking, engine-off operation for the PHEVs, and more efficient operation of the internal combustion engine by supplementing with the traction motor and battery system.

Table 3: Gasoline Fuel Consumption for Conventional Vehicle and Charge Sustaining PHEVs

CYCLE	**Conventional Vehicle**	**Full-Size PHEV charge sustaining**	**Half-Size PHEV charge sustaining**
LA92	3512 J/m 10.98 L/100 km 21.43 mpg	1789 J/m 5.59 L/100 km 42.07 mpg	1862 J/m 5.82 L/100 km 40.42 mpg
UDDS-a	3508 J/m 10.96 L/100 km 21.46 mpg	1535 J/m 4.80 L/100 km 49.03 mpg	1522 J/m 4.76 L/100 km 49.45 mpg

Highway Federal Emissions Test (US EPA)	2199 J/m 6.87 L/100 km 34.23 mpg	NA	NA

In Table 3, the values given for the highway federal emissions test (US EPA) are for the conventional vehicle only and are used here to aid the reader in gaining a feel for the range of fuel consumption.

Figure 3 shows two of the output graphs resulting from the dynamic programming algorithm being applied to the PHEV models. Here, the (near-) optimal engine command is shown versus the tractive effort required between the tires and the wheel. This power measured at the tire-road interface is referred to as the "roadload." Two cycles are run in Figure 3: five UDDS-a cycles to the left (29.4 miles/47.3 km) and four LA92 aggressive urban driving cycles (39.3 miles/63.2 km) to the right.

The engine is not producing power (zero load) for a large portion of the duration of both cycles. When the engine is transmitting power, it appears to be supplementing the traction motor as evidenced by operating commands falling below the line y=x/0.85, where y is the engine command and x is the roadload (i.e., relating roadload to power at the engine shaft via the constant transmission efficiency of Table 1). This engine operation chosen by dynamic programming is a rather complex blending algorithm that minimizes fuel consumption within the constraints given.

We quickly see that duty cycle does make a difference when we contrast the results of the dynamic programming algorithm run over the UDDS-a with those of the LA-92 cycle (Figure 3). Due to the repetition and simplification of the UDDS-a, there is not as much point scatter. We do see similar trends of increased engine usage with roadload. However, we do not see the same amount of point scatter at low engine commands and low roadload as we do for the LA-92.

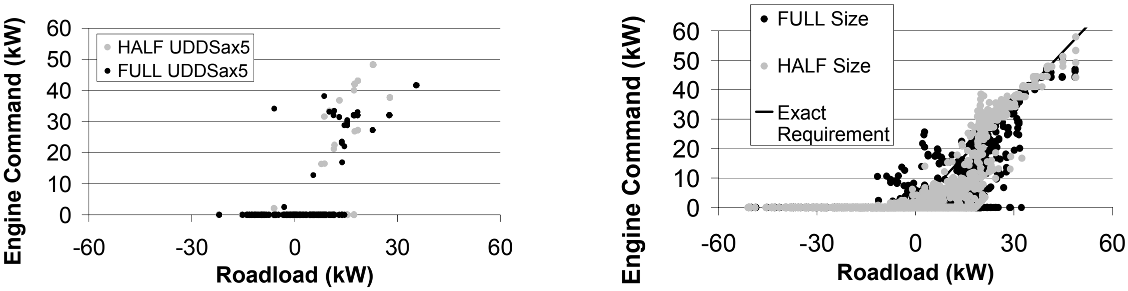


Figure 3: Engine Command versus Roadload over UDDS-a x5 and LA92 x4

The engine commands versus time for the full-PHEV over five UDDS-a cycles and five LA92 cycles appear in Figure 4. There are some similarities in the approaches taken by the dynamic programming algorithm in both cases. First we see a strong emphasis on engine commands in the 20-kW to 40-kW region repeating each cycle iteration (i.e., five times over the five cycle sequence). This is a sensible approach. If it is known ahead of time that engine power must be used to supplement the electric capacity of the ESS, it is best to use the engine when the engine is most efficient. As can be seen from Figure 1, the engine is most effective when at higher power loadings (peak efficiency between 30-50 kW).

Another way to help understand more in-depth what the dynamic programming algorithm is doing is to examine the energy storage system state-of-charge or capacity versus distance. These data inform us of how the battery system is being drawn down—aggressively discharged or at a reduced discharge rate (due to a blending of battery energy with engine power).

Figure 5 (left) shows the energy storage system discharge over three dynamic programming runs: a run of one UDDS-a cycle, a run of three UDDS-a cycles, and a run of five UDDS-a cycles. The full-size PHEV is used on all of the runs. Note that before the vehicle reaches the "electric vehicle centric" range of about 40 km (for the UDDS), the drawdown is completely along an "electric dominant" drawdown path. As distance increases over this “electric vehicle centric” drawdown path, the slope of discharge with distance decreases (i.e., a longer distance is required to discharge the same amount of battery energy). Minimum gasoline consumption is obtained by spreading the battery energy out over the entire distance of the cycle (such that the desired end state-of-charge is reached when the desired range is reached).

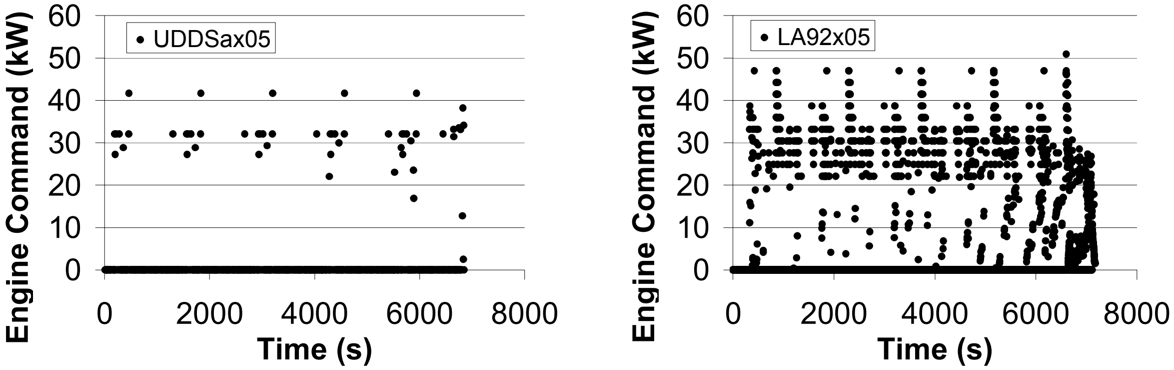


Figure 4: Engine Commands for the UDDS-a and LA92 by Time

The right-hand side of Figure 5 shows the same state-of-charge curve for the LA-92 cycle. This time, the PHEV simulations optimized by dynamic programming over 1 through 5 cycles are shown. In addition, a charge sustaining (CS) run over one LA-92 distance and a run over five LA-92 cycles where the vehicle first has an “electric vehicle centric” discharge followed by charge sustaining operation are shown. In the “electric vehicle centric” case (FULLx05 EV followed by CS operation), the vehicle discharges its electrical energy as fast as possible and then goes into charge sustaining operation. This case provides an interesting contrast to the dynamic programming run over the same distance (FULLx05).

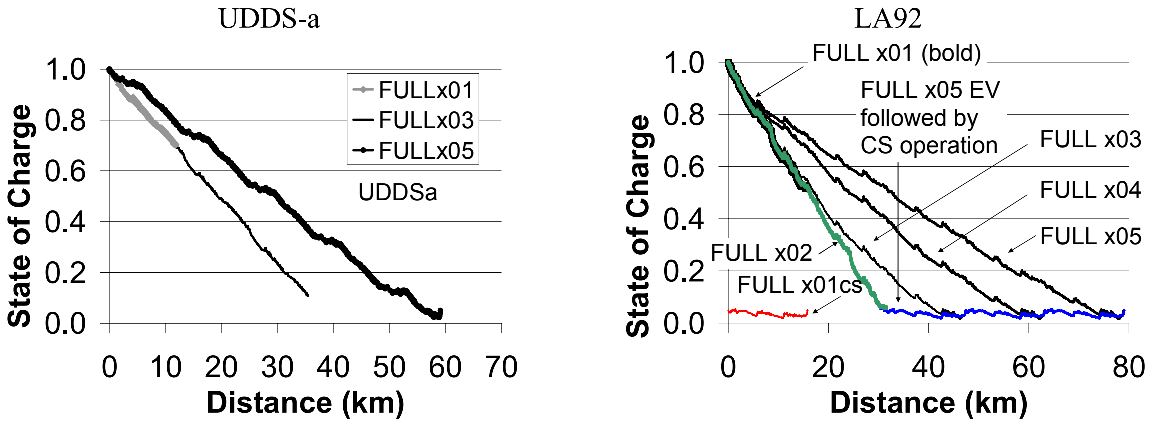


Figure 5: SOC by Distance over UDDS-a and LA92 cycles

In the right-hand-side of Figure 5, for the first couple of LA92 cycles, the vehicle has not yet reached its “all-electric range”. As such, the PHEV can operate in an “electric vehicle centric” mode relying almost exclusively on battery energy. For distances below the “all-electric range”, the dynamic programming algorithm operates the PHEV with an “electric vehicle centric” discharge where possible because this type of operation minimizes gasoline consumption. When the vehicle is asked to operate beyond a range that can be supplied exclusively by battery energy (i.e., beyond the all-electric range), the dynamic programming algorithm blends engine operation with battery discharge to minimize gasoline usage while still driving the requested distance.

In contrast to the dynamic programming strategies for distances above the “all-electric range”, the “electric vehicle centric” strategy draws down as fast as possible and then goes into a charge sustaining mode. Note that charge sustaining operation is around 5% of full (usable) SOC. The results in Figure 5 were exclusively for the "full-sized" PHEV. Let us examine the effect that component sizing and powertrain architecture can have on consumption rates.

Figure 6 shows the consumption rates of gasoline and electricity for the full-size and half-size PHEVs over repeats of the UDDS-a and LA92 cycles. The values for electricity consumption for both full and half-size architectures are quite similar after all-electric range is exceeded (around 40 km on the UDDS-a). This is because both vehicles discharge all of their capacity (albeit in different ways) over the same distance. Electricity consumption also begins to decrease after all-electric range is exceeded. This is because a fixed electrical capacity is being spread out over longer and longer distances. In contrast, gasoline consumption increases after exceeding all-electric range. Note that the full-size PHEV does not require gasoline at any point below its all-electric range for the UDDS-a cycle. On that same UDDS-a cycle, full-size gasoline consumption rates exceed half-size PHEV gasoline consumption rates at higher distances. This is not the case under more aggressive driving such as what is seen on the LA92. The UDDS-a results are due to the smaller motor in the half-size PHEV being better utilized and thus more efficient. Note that fuel consumption rates are not very different between the full and half-size PHEVs for most distances. Full-size and half-size electricity consumption rates are nearly identical after all-electric range is met. The largest disparity is under aggressive urban driving prior to all-electric range being met. However, in terms of absolute fuel usage, the fuel usage of the half-size PHEV is still only about 1/9th the consumption rate of a conventional vehicle over the same cycle.

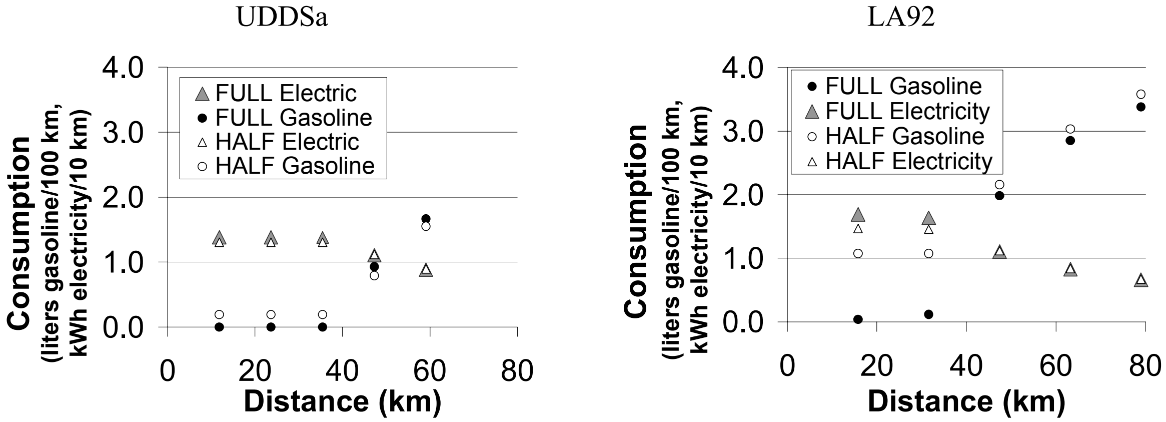


Figure 6: Fuel Consumptions of PHEVs over UDDS-a and LA92 Cycles

Figure 7 shows us one of the key areas of impact for PHEV technology—gasoline fuel usage by distance. The set of graphics in Figure 7 are run for the half and full-size PHEV vehicle over the UDDS-a (mild urban driving) cycle. Each curve on the figure is the result of a dynamic programming run optimized for the given distance. That is, for example, the curve labeled "HALFx3" is the fuel consumption minimized by the dynamic programming algorithm to have the lowest net fuel consumption after 3 UDDSa cycles back-to-back. This distance aspect is key to understanding what is going on with the dynamic programming control of PHEVs. In this case, the dynamic programming algorithm has *a priori* knowledge of the cycle and distance to be run and shows us the optimum control under that circumstance. For distances above the "all-electric range," the operation is a "blending strategy" that blends engine usage with motor usage so as to minimize fuel consumption while meeting the drive cycle trace. This blending is in addition to that required due to component size limitations such as when an acceleration event requires more power than the traction motor can handle in isolation and thus the engine assists.

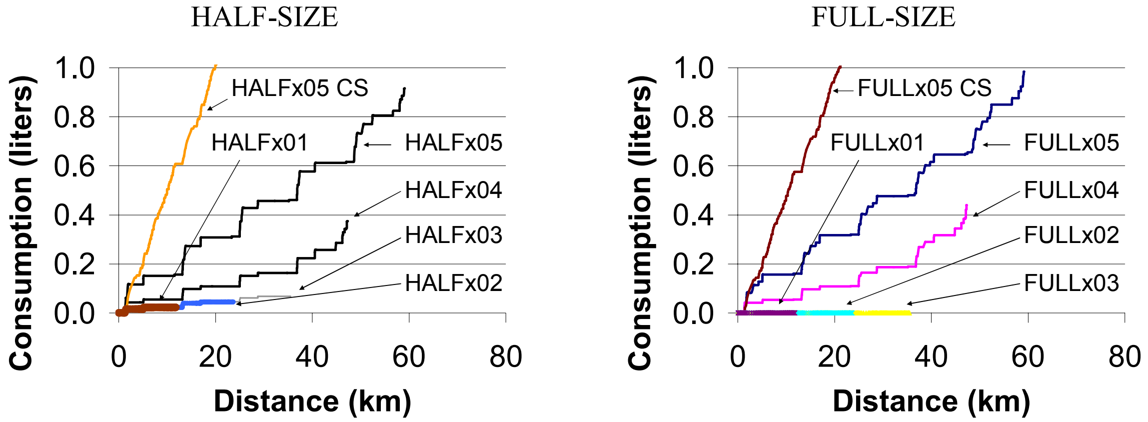


Figure 7: Gasoline Consumption of Half and Full-Size PHEVs over UDDS-a Cycles

What is key to note here is that for both the half and full-size PHEVs, a fuel consumption optimally blended to have minimum fuel consumption at a given target distance does not necessarily have the minimum consumption at other distances. Figure 8 further expands upon this point by displaying gasoline consumption results for the LA92 contrasted with an "electric vehicle centric" control strategy. All runs change to charge sustaining operation after reaching their target distances. The charge sustaining control is optimized by dynamic programming to minimize fuel.

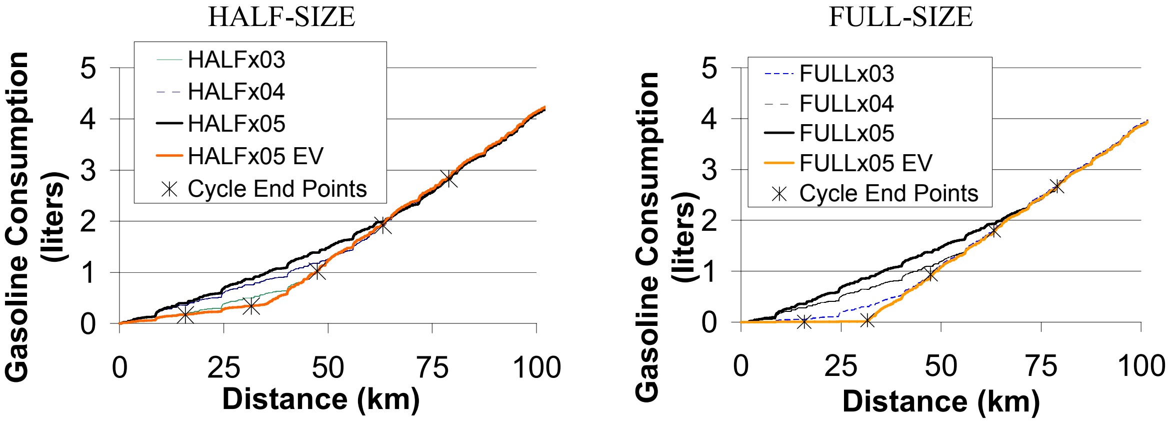


Figure 8: Gasoline Consumption over LA92 for Half- and Full-Size PHEV

Figure 8 shows the results of dynamic programming runs applied to multiple distances of the LA92 driving cycle. The designation "FULLxN" refers to the full-size PHEV optimized by dynamic programming to run for a number of LA92 cycles equal to N. Dynamic programming for N cycles operates the vehicle to have near minimum fuel consumption for the given distance.

Figure 8 also contains the results of the PHEV run in an "electric vehicle centric" mode (labeled "EV" in the figure) where the engine is commanded to be off unless doing so would cause the vehicle to not meet the cycle speed-time trace. Thus, simply put, "use electricity to power the vehicle if at all possible and supplement with the engine if the motor does not have enough power to meet the cycle speed-time trace." When the vehicle has run its target distance, the PHEV begins to run in charge sustaining mode. That is, the PHEV begins to run similar to a conventional HEV where no significant net discharge of the energy storage system occurs over time or distance. This can be seen clearly for the "FULLx03" case where the vehicle has one of the lowest energy consumptions of the "blended" modes until one LA92 distance and then changes over to charge sustaining mode.
As can be seen from Figure 8, gasoline fuel consumption for the "electric vehicle centric" control is nearly equivalent in all cases to the dynamic programming control set to minimize fuel consumption over a specific distance. This is because we are continually running the same cycle back-to-back and thus it doesn't matter if one uses the electrical energy all at once at the beginning or spread out

throughout the cycle. The equivalency between strategies would not necessarily be the case for varied driving patterns though the effect of driving pattern variation has not been examined in this study.

Now, let us consider these dynamic programming results in the context of what can be practically implemented in real life. There are two general strategies that have been presented: a “blended” engine/motor strategy and an “electric vehicle centric” strategy. The “blended” mode is what the dynamic programming algorithm optimized to give minimum fuel usage for a given distance most closely resembles. The engine is run at the most opportune times to minimize fuel consumption. In the “electric vehicle centric” strategy, focus is given to supplying transportation energy with electricity and the engine is only used when necessary to meet vehicle performance constraints.

Note that for distances below the PHEV’s electric range, the dynamic programming algorithm chooses an “electric vehicle centric” strategy as this minimizes fuel usage for any range below the electric range. That is, if we know we will be running less than the all-electric range of the vehicle, the “electric vehicle centric” strategy is near optimal. For distances longer than the PHEV’s electric range, a blended strategy is chosen by dynamic programming. However, let us consider the “cost of being wrong” in terms of choosing a control strategy for trip distances above the electric range of the vehicle. Figure 8 shows us that a vehicle with a “blended” strategy optimized for an intended 80 km of intense urban driving would use more fuel than the “electric vehicle centric” strategy all the way up to above 70 km of driving distance. It should be noted that the “electric vehicle centric” control strategy benefits from a charge sustaining control optimized by dynamic programming. However, so does the actual blending mode control. Thus, even if we imagine adjusting the fuel consumption rates upwards during both blended charge depleting operation and charge sustaining operation, the point is still clear: a vehicle operating in blended mode that deviates from the target distance uses more fuel than a vehicle using an “electric vehicle centric” approach. Therefore, the “electric vehicle centric” mode is essentially the optimal fuel consumption case over most of the distance. In contrast, the “blended” mode is optimal for specific distances but non-optimal for others.

4 Conclusions

This study shows that a half-size PHEV using a smaller motor and low power-to-energy ratio batteries has nearly the same fuel consumption of a full-size PHEV (and in some cases, can have an even lower fuel consumption), but uses components that can be of lower cost. The biggest disparity in gasoline fuel consumption rates is at low distances (below the all-electric range of the PHEV) over aggressive driving cycles where the engine is often forced to assist when meeting roadloads. Even so, under these conditions, the absolute fuel usage is low (~1/9th the fuel consumption of a conventional vehicle for the case of the LA92 cycle).

Furthermore, this study shows that under optimal control, a blended control strategy uses approximately the same amount of fuel as an “electric vehicle centric” approach for known target distances (and constant driving patterns). However, the penalty for “guessing wrong” on the target distance and type of travel can be high for a blended strategy. That is, a control strategy optimally blended to have minimum fuel consumption at a given target distance does not necessarily have the minimum consumption at other distances. Thus, it is typically better to run with an “electric vehicle centric” control strategy that emphasizes using electricity to supply vehicle power demand to the extend possible within the limits of the motor size.

This work was conducted over urban driving cycles for PHEVs with specific energy capacities. Further work should cover other energy capacity sizes and types of driving including the effect of varied driving patterns along a given trip. Additionally, the details of engine on/off including cranking energy and emissions implications should be addressed.

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