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Impact of Real World Drive Cycles on PHEV Fuel Efficiency and Cost for Different Powertrain and Battery Characteristics

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Abstract

For the past couple of years, Plug-in Hybrid Electric Vehicles (PHEVs) demonstrated their ability to significantly reduce petroleum consumptions. However, more than any other vehicle powertrain, their benefits are dependent on the driving cycles from both an aggressiveness and distance point of view. In this paper, two powertrain configurations will be defined. A power split configuration will be used for low battery energy and a series configuration for high battery energy. For each vehicle we will evaluate several control strategies, including electrical dominant and blended, on real world drive cycles. A conventional vehicle will be defined to use as a baseline. The trade-off between fuel displacement and cost will be evaluated for each option.

Keywords: PHEV, modelling, simulation

1 Introduction

PHEVs have demonstrated great potential with regard to petroleum displacement. Since the benefits of PHEV technology rely heavily on the battery [1], the development of new generations of advanced batteries with a long life and low cost is critical. To satisfy this goal, the U.S. Department of Energy (DOE), as part of the FreedomCAR and Fuels Partnership, is funding the development and testing of battery technologies.

Previous studies that focused on the impact of other standard cycles [6] or powertrain configurations [7] demonstrated the need to

further evaluate driving behaviors. Argonne has been working in collaboration with the U.S. Environmental Protection Agency (EPA), which has been interested in real-world fuel economy in the past few years [8]. This paper addresses the impact of real world drive cycles on PHEV fuel efficiency and cost.

2 Vehicle Description

The vehicle class used represents a midsize sedan. The main characteristics are defined in Table 1.

Table 1: Main Vehicle Characteristics

Glider mass (kg)	990
Frontal area (m ²)	2.2
Coefficient of drag	0.29
Wheel radius (m)	0.317
Tire rolling resistance	0.008

Two vehicle configurations were selected depending on the degree of electrification:

- An input power split with a fixed ratio between the electric machine and the transmission, similar to the Camry HEV, was used for HEV and for PHEV with low energy (4 and 8kWh total battery energy)
- A series engine configuration was selected for PHEVs with large energy (12 and 16 kWh battery energy cases).

3 Component Sizing

To quickly size the component models of the powertrain, an automated sizing process was developed [9]. A flowchart illustrating the sizing process logic is shown in Figure 1. Unlike conventional vehicles, which have only one variable (engine power), PHEVs have two variables (engine power and electric power). In our case, the engine is sized to meet the gradeability requirements.

To meet the all-electric range (AER) requirements, the battery power is sized to follow specific driving cycle while in all-electric mode. The batteries for the power split configurations are sized to follow the Urban Dynamometer Drive Schedule while the series configurations are based on the more aggressive US06. We also ensure that the vehicle can capture the entire energy from regenerative braking during decelerations.

In previous studies [1, 3, 4, 5], the battery energy was sized to meet required AER. In this case, four battery energy values were selected: 4, 8, 12 and 16 kWh total.

Vehicle mass is calculated by adding the mass of each component to the mass of the glider. The mass of each component is defined on the basis of its specific energy and power densities

To maintain an acceptable battery voltage (around 200 V), the algorithm will change the

battery capacity rather than the number of cells to meet the AER requirements. To do so, a scaling algorithm [8] was developed to properly design the battery for each specific application.

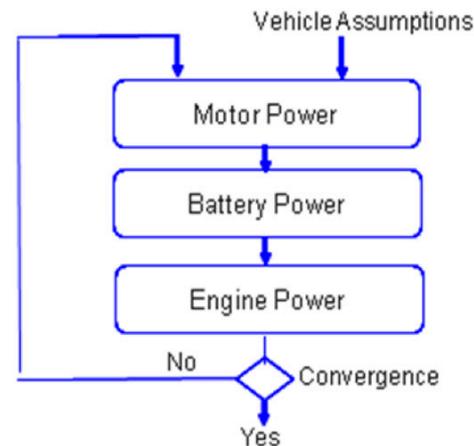


Figure 1: Process for Sizing PHEV Components

Finally, the PHEV will operate in electric-only mode at a higher vehicle speed than will regular hybrids. The architecture therefore needs to be able to start the engine at a high vehicle speed. In the power split configuration, the generator is used to start the engine. Because all of those elements are linked to the wheels via the planetary gear system, one needs to make sure that the generator (the speed of which increases linearly with vehicle speed when the engine is off) still has enough available torque — even at speed above 50 mph— to start the engine in a timely fashion.

For the HEV powertrain, the battery is sized to capture the regenerative braking energy from the UDSS. The engine and both electric machines are sized to meet both gradeability (6% at 65 mph at gross vehicle weight) and performance requirements (0-60 mph under 9 sec). The control strategy used has been validated against vehicle test data from ANL's Advanced Powertrain Research Facility.

4 Drive Cycle Description and Analysis

The real world drive cycles have been measured by the U.S. EPA. In 2005, more than 100 different drivers in Kansas City participated in the study. The user vehicles (model year 2001 and later) were instrumented and their driving statistics were collected for the duration of a day. While several

measurements were taken, only vehicle speed was used as part of this analysis. Speed was collected on a second-by-second basis independently through the on-board diagnostic (OBD) port as well as from a GPS device [10]. The OBD speed data was favored over the GPS when both were available. Data was collected on conventional as well as hybrid vehicles, but for reasons of simplicity, we have chosen to examine the speed from the conventional vehicles only, though there were minor differences in their driving [11]. Figure 2 shows an example of real world drive cycles. The maximum acceleration and deceleration of each trip were analyzed to ensure data validity.

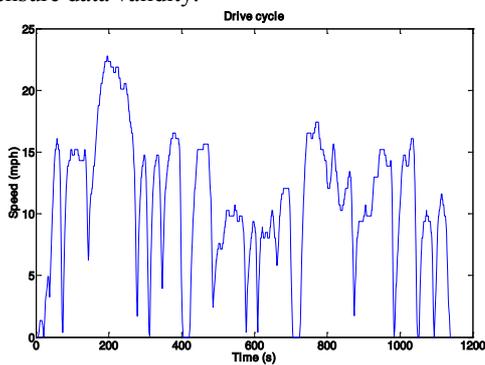


Figure 2: Example of Real-World Drive Cycles

Figure 3 shows the distribution of the distance during daily driving. Fifty percent of the drivers drive more than 40 miles per day. The cumulative driving distance computed from the National Household Travel Survey (NHTS) data. It appears that a greater number of short trips characterize the NHTS curve.

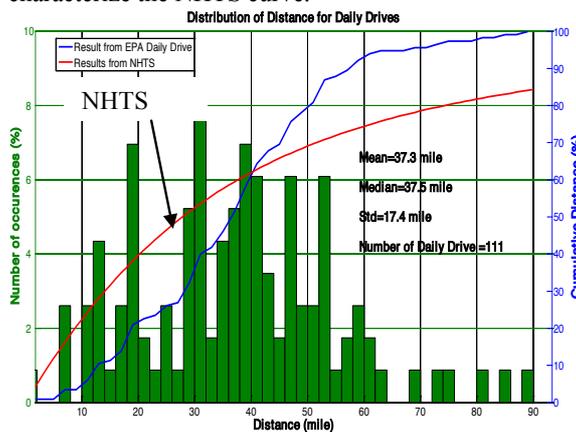


Figure 3: Distance Distribution of Daily Driving

Each daily drive can be decomposed into several trips. A trip is defined by events for which the

driver turns the ignition on and off. Figure 4 shows the distance distribution of each trip. An average trip is 11 miles.

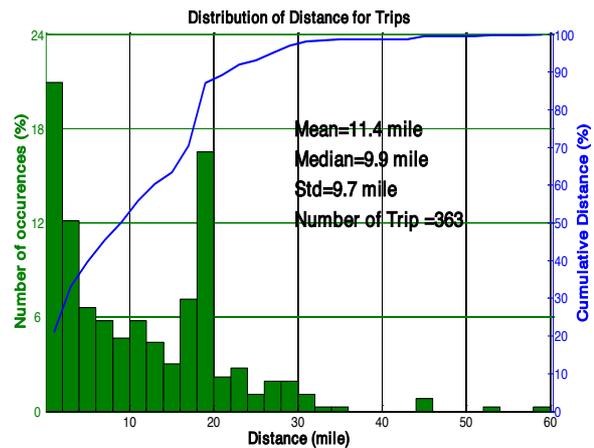


Figure 4: Distance Distribution of Each Trip

5 Fuel Efficiency Results

5.1 Reference Conventional Vehicle

Each vehicle is simulated on all daily drive. A histogram showing the distribution of the results can be generated as shown in Figure 5. The mean value achieved for the reference vehicle is 6.4 l/100 km.

To compare different powertrain configurations, a kernel density function is defined.

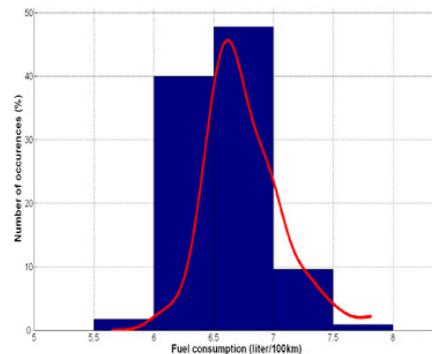


Figure 5: Conventional Vehicle Fuel Economy Distribution

5.2 Drivetrain Configuration Comparison

Different control strategies were implemented depending upon the powertrain configuration considered. Each control option is briefly described below.

EV/CS (Thermostat) Strategy - The EV/CS control strategy was implemented for the series configuration. The controller has been designed to drive as long as possible by using energy from the battery, which depletes its state-of-charge (SOC) from 90% SOC to 30% SOC. The engine turns on only if the road load exceeds the power capability of either the battery or the motor. Once the battery reaches charged sustaining (CS), the engine is used as a thermostat to regulate the SOC.

Load Engine Power Strategy (Load following) - A power threshold, depending on the battery state-of-charge (SOC), is used to turn the engine ON. As a result, the engine can be turned ON during charge depleting (CD). To maximize charge depletion, when operating, the engine only provides the requested wheel power without recharging the battery.

Optimum Engine Power Strategy - Similarly to the previous control, the engine is turned on based on a variable power threshold. However, the strategy attempts to restrict the engine operating region close to the peak efficiency of the engine. As a result, the engine might be used to recharge the battery during charge depleting.

These different options were selected to provide an acceptable trade-off between the number of engine ON and fuel efficiency.

Figure 6 shows the mean values of both electrical and fuel consumptions for the different powertrain options. As one notices, the lowest fuel consumption reductions are achieved for the largest electrical consumptions. As demonstrated in previous studies [12], the fuel and electrical consumptions have a linear relation.

When analyzing both series configurations, a smaller fuel consumption is achieved when using a 16 kWh total battery energy compared to a 12 kWh.

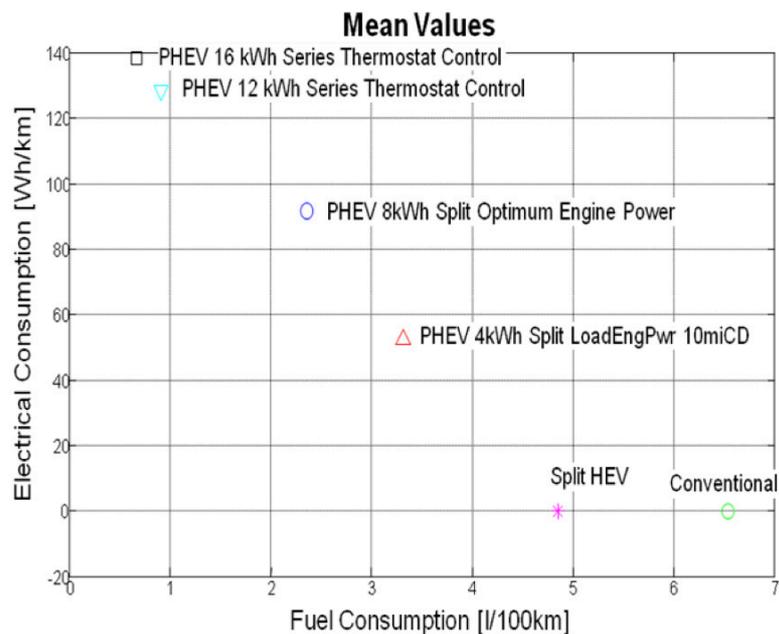


Figure 6: Comparison of the Mean Values for the Different Configurations Considered

Figure 7 provides the kernel distribution curves for the fuel consumption of each powertrain

option. One notices that with the increases of available battery energy, the standard deviation

increases. This is due to the fact that the engine operation becomes less dependent to the drive cycle with increased available battery energy.

For the largest battery energy, a significant portion of the drive cycles are driven in electric only mode.

Figure 8 provides the kernel distribution curves for the electrical consumption of each powertrain

option. The lowest battery energy (4kWh) has the lowest standard deviation. This can be explained by the fact that the battery is used mainly for low power applications due to the control strategy selected. Both medium battery energy cases (8 and 12 kWh) provide the widest standard variation as the battery is both used for low and medium power requirements.

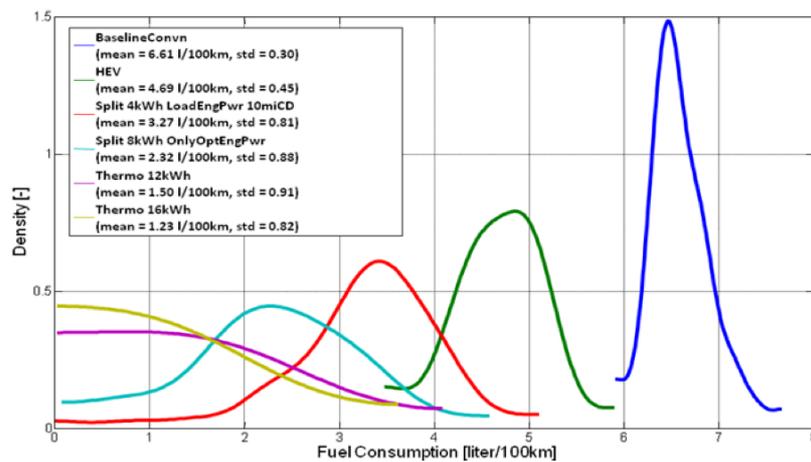


Figure 7: Fuel Consumption Comparison

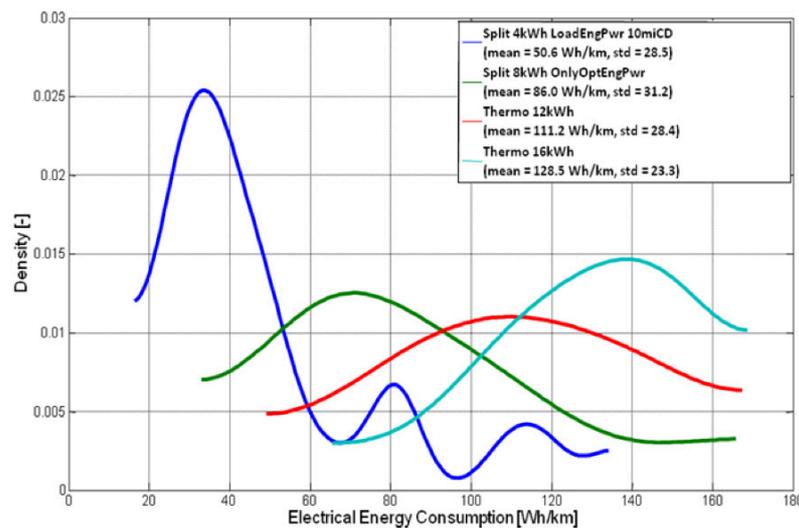


Figure 8: Electrical Consumption Comparison

5.3 Impact of Distance on Consumption

Figure 9 provides the fuel consumption for each daily drive and vehicle powertrain. The total volume of fuel consumed by each drivetrain

configuration for running all the cycles was computed and is summarized in Table 2

Table 2: Fuel Consumed Total

	Volume (L)	% decrease vs. conventional
Conventional	454	
HEV	328	27.6
PHEV 4kWh	238	47.5
PHEV 8kWh	172	62
PHEV 12kWh	99	78
PHEV 16kWh	54	88

As one notices, significant gains are achieved with the HEV configuration. These gains are however lower than those usually found when simulating standard drive cycles.

An additional 20% is achieved by using a 4kWh battery. The gains from adding further battery capacities decrease when going from 8 to 16 kWh with only a 10% increase from 12 to 16 kWh.

Figure 10 provides the electrical consumption for each daily drive. For daily drive with short electrical distances (less than 15 miles), the electrical consumption of PHEVs is similar across powertrain options. This is likely due to the fact that these cycles are characterized by low power demand and can consequently be mostly performed in all electric mode.

The largest discrepancies are noticed for medium distances (15 to 25 miles). These drive cycles are characterized by both low and large power demands. As a result, while the power split 8kWh option will lead to engine ON, the series configurations will continue to operate in all electric mode, resulting in higher electrical consumption. This is consistent with the electrical consumption distribution shown in Figure 8.

Finally, for the longest distances, both series configurations provide similar behavior since the control strategy favors the use of electrical energy.

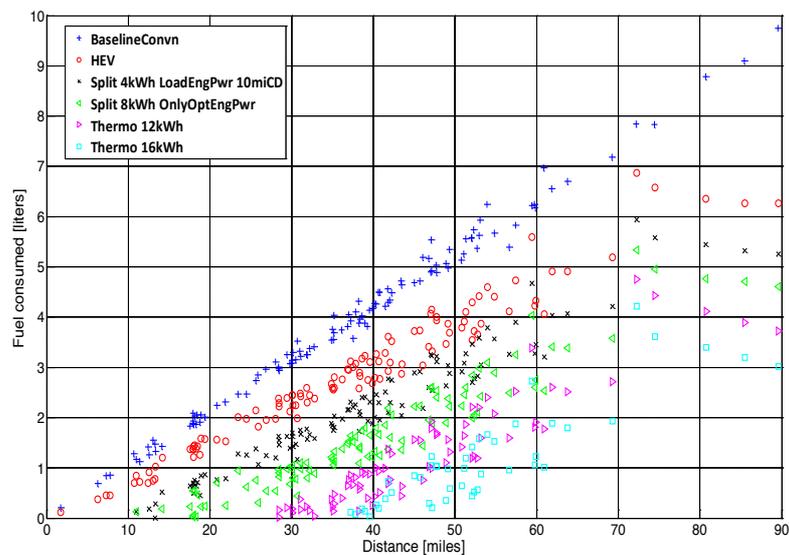


Figure 9: Fuel Consumption as a function of Distance

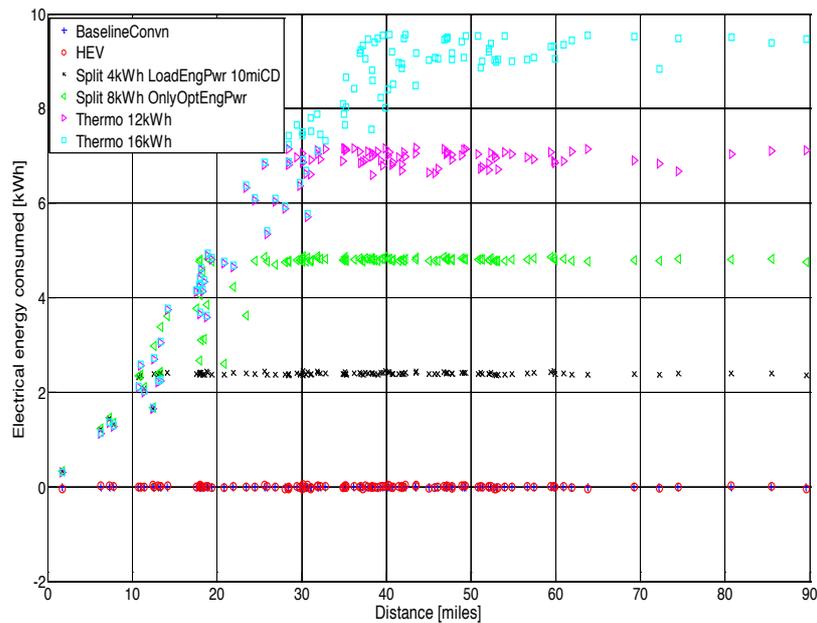


Figure 9: Electrical Consumption as a function of Distance

6 Cost Benefit Analysis

The cost of the vehicle is defined by the size of the different component, both for power and energy. The cost assumptions, defined to represent short to medium term technologies, are provided in Appendix 1. The vehicle costs used to calculate the payback are presented in Table 3.

Figure 10 shows breakeven lines for the assumptions considered. The HEV breaks even at 7.5 years while the PHEVs range from 8 to 12.5 years.

Figure 11 shows the payback as a function of distance for the different vehicles. The results below are provided for an electrical cost of 0.09\$/kWh and a fuel cost of \$4/gallon. As one notice, a longer daily drive distance can significantly reduce payback time.

In addition, HEVs are more cost effective than PHEV 4kWh for daily driving longer than 30 miles, but the order is reversed for shorter distances.

Table 3: Vehicle Cost

Parameter	Vehicle Cost (\$)
Conventional	17245
HEV	20029
PHEV 4kWh	21881
PHEV 8kWh	23709
PHEV 12kWh	27487
PHEV 12kWh	29338

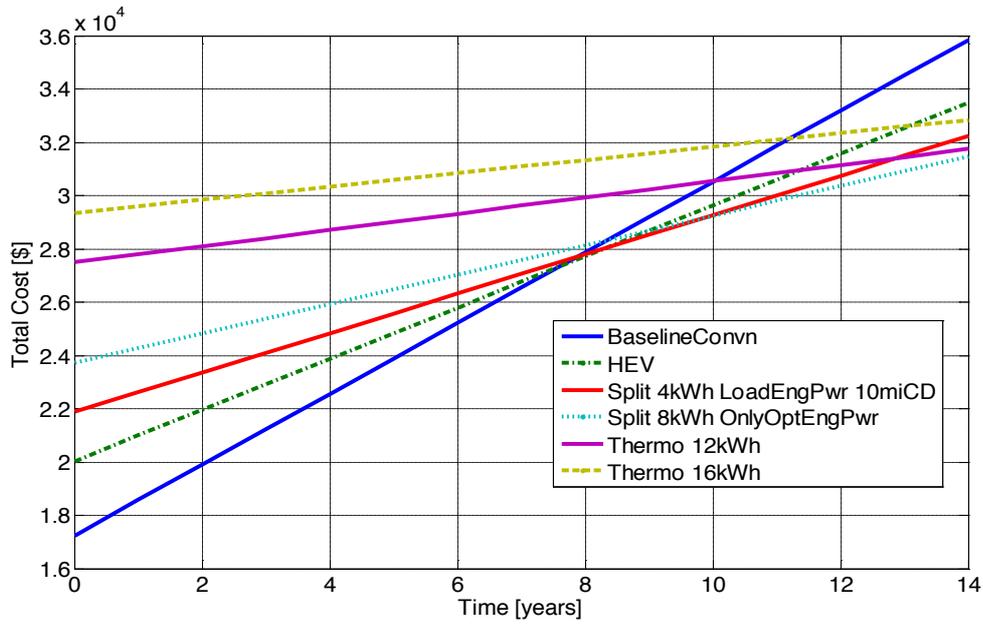


Figure 10: Breakeven Line

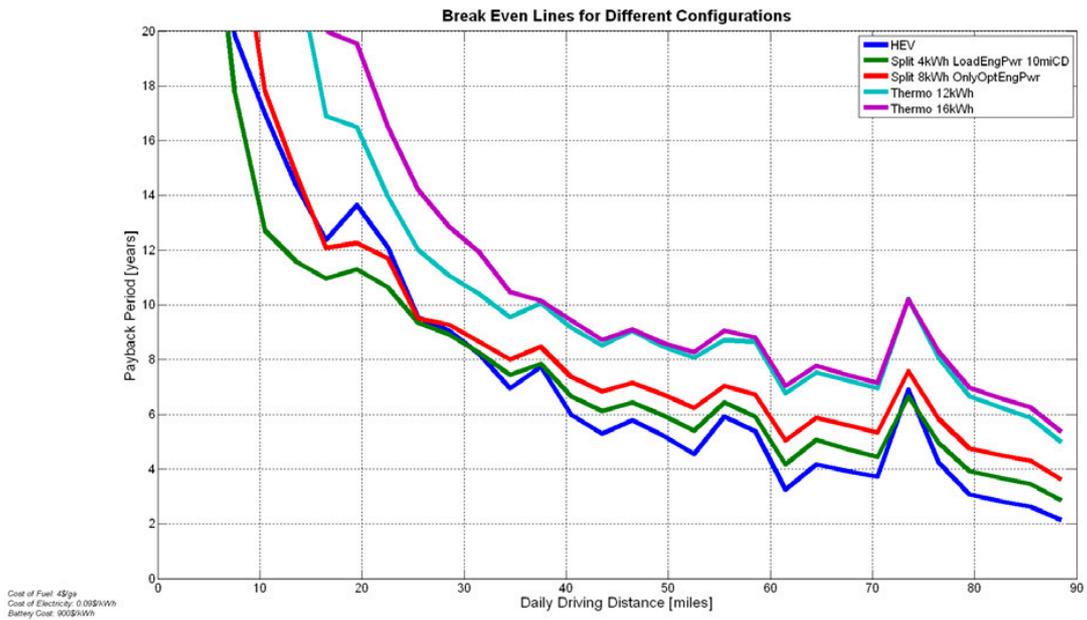


Figure 11: Payback as a function of Distance

7 Conclusion

Different powertrain configurations, including conventional, HEVs and several PHEVs have been simulated on more than 100 real world daily drive cycles. The power split configuration was selected for the HEV and PHEV 4 and 8kWh cases, while the series option was used for the largest battery energies (12 and 16 kWh).

The simulation results demonstrated significant fuel economy gains both with HEVs and PHEVs with fuel displacement increasing linearly with available electrical energy.

However, it appears that the benefits of adding 4kWh of battery energy seems to decrease from 12 to 16 kWh due to the distribution of the daily driving distances.

Since the drive cycles have different characteristics based on distance, the benefits of each vehicle configuration depend on how far the vehicle is driven. While the electrical consumption is similar for small and long driving distance, the main differences occur during medium trips.

Based on the assumptions considered, the cost of PHEVs remains high. In addition, achieving the same payback period between two battery pack options requires longer driving distances for larger battery packs.

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APPENDIX 1 – Cost Assumptions

Parameter	Value
Engine	$300+3*\text{Power}+275*\text{Number cylinder}$
Power Battery	40 \$/kW
Energy Battery	$380*\text{Total Energy} + 25*\text{Peak power}$
Electric Machine (EM)	7 \$/kW
EM Controller	9 \$/kW
Battery Charger	\$800