Dual-Source Energy Storage – Control and Performance Advantages in Advanced Vehicles

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Abstract

This paper introduces a methodology for evaluating and segregating load requirements and characteristics to size hybrid energy source/storage elements for handling the types of loads for which they are best suited. This work focuses on investigating the use of a dual-source battery and ultracapacitor pack in place of the seemingly unattainable (in satisfying cost, power, energy, and reliability requirements) single-battery solution that is being sought for hybrid electric applications. However, this methodology is general enough to be applied (with adequate knowledge of load profiles) to any application with two or more source/storage elements. A prerequisite for segregating loads is to use "expert" knowledge to characterize the various sources' strengths and weaknesses. Component role segregation should facilitate (1) various control method evaluation for real-time implementation of the multi-source solution (without prior profile knowledge), and (2) optimization routines to further adjust component sizing and control variables to maximize fuel economy objectives and minimize mass, volume, and (possibly) cost objectives. This paper provides the general methodology and an example battery and ultracapacitor combination for a midsize hybrid electric vehicle.

Keywords: Battery Management, Battery Pack, Configuration, Control System, Double-layer Capacitors, Efficiencies, Energy Storage, Hybrid Strategy, Load Management, Optimization, Response Time, Simulation, Super Capacitor, Ultra Capacitor

1. Introduction

The development of hybrid energy sources/storage (gaseous, hydrogen, electric, hydraulic, pneumatic, etc.) in vehicles introduces a unique opportunity for segmenting the types of loads in automotive applications. The extremely wide variation of automobile uses presents load requirements with significant variations: thermal (climate), gravimetric (loading), duration of drive cycles, and transient magnitudes and frequencies during cycles. Overall, two pertinent types of load variations occur in automobiles and trucks:

1. A variable power-to-energy (P/E) ratio requirement – this is closely related to the event's time constant, as its units are 1/s. The P/E provides a good method to distinguish transient behavior with higher values representing transients (in power magnitude in combination with brevity). In segregating average from transient P/E requirements, we will use the time constant as the primary variable to differentiate these loads. The variable P/E ratio, in conjunction with efforts to hybridize vehicle powerplants, results in the opportunity to source the variable P/E ratio (time constant) requirements from appropriately suited power sources.
2. The duty cycle at various transient power levels – The duty cycle is P/E-associated, but measures whether the P/E is a good estimate of the load's energy requirements over longer durations. For example, a transient may occur often enough that the energy storage component cannot be recharged before the next occurrence. In this case the duty cycle could indicate that the component would need to be sized for multiple transients. In other words, evaluating the duty cycle is an important step in determining whether an energy storage component is a good fit for a specific transient or whether the overall energy requirement, because of the transients' pervasiveness, will require a component with a lower P/E ratio (higher time constant). The duty cycle will not be defined in its traditional electrical

engineering sense, but we will discuss the duration of peak power events and the overall energies required (integration of the power events).

This work focuses on evaluating the suitability of a dual-source (multiple P/E ratio) battery and ultracapacitor pack in place of the do-all single-battery solution that is being sought for hybrid electric applications. First, the component strengths will be discussed, then the types of duty cycle loads for a standard mid-sized vehicle will be evaluated. Finally, the conflicting trade-offs for sizing the components will be discussed. Further load analysis can be conducted for the various auxiliary loads; however, only constant auxiliary load power levels were included in this study.

2. Analysis Assumptions

Average characteristics of a standard midsize passenger car were used to develop vehicle power load profiles. The vehicle assumptions and performance requirements can be seen in Table 1 and Table 2. The vehicle's power profiles were developed by simulation in ADVISOR$^{\text{TM}}$ with a 10-Hz data stream [1]. The simulated power profiles are a maximum acceleration, a maximum sustained grade, the EPA highway cycle, two back-to-back city (UDDS) cycles, and the US06 cycle [2]. The first UDDS cycle is shown in Figure 1 as an example power profile. The simulated vehicle's maximum and average power characteristics over the various drive cycles are listed in Table 3.

To evaluate the trade-offs between ultracapacitors and batteries, the energy differences between the devices must be recognized. Table 4 summarizes the available energy range typical of traction batteries and ultracapacitor packs. The assumptions are discussed next.

Traction batteries are typically cycled at a delta state-of-charge (SOC) of about 20% for relatively conservative use, to about 60% for more aggressive use. Also, cycling batteries around a center point of roughly 50% SOC is often most efficient. For this paper, the traction battery is assumed to be cycled around 50% SOC with a delta SOC of ±25%. In this respect, the available energy from the battery, in Watt-hours (Wh), is roughly 50%. Assuming an average pack voltage of 300 V and available battery capacities of 5–50 Ah, the batteries provide an energy range of 750–7,500 Wh. See Equation 1 for details.

In contrast, carbon-carbon electrode-based ultracapacitors are typically cycled at 50%–100% SOC. Often an over voltage capability will be specified for ~110% SOC operation, but in general the top-end 50% SOC range enables the use of 75% of the ultracapacitor's Watt-hours. The voltage range of ultracapacitors is typically 0–2.5 V, resulting in a 50%–100% voltage range of 1.25–2.5 V. Again assuming a 300 V midpoint voltage, the voltage range of the 160-cell ultracapacitor pack would be 200–400 V. Available ultracapacitors' capacitance ratings vary from 10 Farads (F) to 5000 F per cell. Cell packaging penalties become more significant below about 500 F. Thus, the resulting energy range that ultracapacitors provide is 52–520 Wh. See Equation 2 for details.

3. Role Specialization: Playing Off Component Strengths

Various hybrid vehicle design studies have dealt with using the steady-state operational strengths of the internal combustion engine [ICE]. Series and parallel hybrid studies have suggested operating the ICE at high loads because of its inherently higher efficiencies in this region [3, 4]. Significant downsizing of the ICE has also been proposed so the ICE is sourcing the average load in a drive cycle [5]. However, mainstream applications have tended toward parallel designs that maintain the engine as the primary mover [6]. Nonetheless, the Toyota Prius engine control strategy also aims to operate the engine in higher load/efficiency regions. Gearing and throttle control details will not be dealt with in this paper, but the underlying convention for sizing and typically operating the engine in high-load, steady-throttle, and mid-rpm range will be applied. Thus, the aim of the vehicle power profile analysis is to determine the modes of operation that require continuous power flow in-line with efficient engine operational points.

Nonetheless, the hybrid energy storage load-averaging concept could still be applied for a vehicle with a completely different ICE strategy, following analysis of its unique energy storage requirements. One drawback of dual-scource energy storage is that voltage must be regulated for one or both energy storage packs to match the voltage of the other pack or the DC-link voltage.

The importance of operating the batteries in efficient and reliable operating regions is often downplayed in hybrid vehicle design. However, as one of the most trouble-prone components in the electric drive, the operating regions with which the battery is tasked are of paramount importance for reliable, efficient operation over a long operating life. The factor that presently influences many control strategies is the SOC operating range. Current systems are designed with the SOC set to relatively narrow operating ranges of roughly 60%–<20% (from an amp-hour or coulombic perspective). Narrower ranges are associated with longer cycling life. The specific SOC limits, 40%–80% SOC for example, are typically determined based on pulse power capability and efficiency [7]. Other important operational factors include temperature, electrochemical equalization, and current magnitude. All these conditions are at the very least monitored in most design prototypes. However, the battery manufacturers often carefully increase the current magnitude to expand power capability for the power profile. Peak currents are supplied at the expense of lower efficiency (relative to efficiency at lower currents) and increased heating rate. They can also cause accelerated aging. To be complete, the electric motor/battery system can generally handle peak power pulses more efficiently than the ICE, and the battery can then recapture the energy through peak or gradual regenerative charging events. However, in attempting to segregate the vehicle power profile for the most efficient operation, we may find that many batteries are better suited to longer duration, medium power events that have higher energy demands, instead of the peak power events with lower energy requirements.

Ultracapacitors (double layer capacitors, electrochemical capacitors, and supercapacitors) have seldom been included in prototype hybrid electric vehicles because of pricing and energy density issues. However, in the last two years the prices have dropped steadily, and energy densities have improved incrementally. Ultracapacitors also have some safety issues that need to be addressed, such as whether acetonitrile, the popular electrolyte solvent in Europe and the United States, is safe in vehicle use. Yet, some Japanese manufacturers are starting to show that more inert electrolytes can be effectively used with reasonably competitive power and energy performance [8]. The main advantages of ultracapacitors are their high power and cycling capability. They can be charged and discharged at very high current rates and are more efficient than batteries at these rates. The two main reasons an ultracapacitor can accept and supply high-rate currents more efficiently are its lower series resistance (ESR), relative to batteries, and its non-Faradaic method of storing charge through a fairly ideal double layer capacitance [9]. Thus, ultracapacitors may handle challenging power transients in vehicle power profiles more efficiently and with more suitable energy content.

4. Load Specialization: Dividing and Conquering the Power Profile

The goal of load specialization is to segment the various power profiles in drive cycles into appropriate time and power segments. In accordance with the component selection detailed above, the segments of interest are: steady state loads for the engine (or for the fuel cell); intermediate loads, of magnitude and time frame, for the batteries; and loads with peak magnitudes for short, transient time frames for the ultracapacitors.

The power segmentation performed in this paper is based on an anti-causal, zero-phase, FIR (finite impulse response), digital averaging filter. The anti-causal, zero-phase quality enables us to eliminate a typical filter’s phase distortion by time reversing the filtered sequence and running it back through the filter. This aspect of the filter was used because the full power profile knowledge is known before the filter is applied. This implementation would not be possible in real-time applications. However, the real-time control would probably need to adjust the filtered set point for operational limitations, such as finding maximum ICE driveline efficiency at a specific temperature, gear ratio, etc. The end result of real-world implementation can be relatively close to this software implementation of the zero-phase averaging filter through the use of one of a variety of methods to ramp up the ICE during the main filter's longer time constant (phase-lagging) response [10].

The FIR averaging quality was chosen so a number of time constants (see #1 in the introduction) could be evaluated for the gasoline engine and for the batteries. The operational time constants vary from 10 min to 0.5 s. The ultracapacitor set point was unfiltered, and thus simply made up the difference between the required power and what the ICE and batteries were tasked to supply. A wide range of time constants were parametrically evaluated.

4.1 Evaluating the Load Averaging Capability for the Internal Combustion Engine

Initially, we will look at the impact of setting the ICE power request to a specific filter time constant. This analysis (Figure 2) illustrates how the peak and average ICE power over the various cycles changes with varying filter time constants. The limiting cycle initially appears to be the peak acceleration power point; however, this requirement does not need to be sustained except for periods of approximately 10 s for a 60 mph acceleration and in a more extreme case 30 s for an acceleration to 90 mph. As long as we assume that the peak acceleration duty cycle is much less than 50%, then supplementing accelerations should be a suitable task for the energy storage system. In this case, the true limiting cycle is the 6.5% grade test at a constant 65 mph. The grade test is sustained for 20 min, and for all intents and purposes the vehicle should be able to sustain this state for a continuous duration. Thus, setting the ICE power request at a filter time constant longer than 10 s has little effect on engine downsizing. The required ICE peak power can be reduced from approximately 100 kW for the <10 s time constant cases down to approximately 55 kW for the time constant settings longer than 10 s. However, we may still want to operate the engine with time constants longer than 10 s from the standpoint of ICE throttle/efficiency control and battery time constant operation, the latter of which relates to battery and ultracapacitor sizing.

Although sweeping the ICE filter time constants can allow the engine to be downsized, it also results in new energy storage power and energy requirements. The engine power does not necessarily scale up or down with the required vehicle power (Figure 3), because of the load averaging that the control filter is accomplishing. Thus, the energy storage system must be capable of supplying assist power during transient acceleration events and accepting power during ICE based charge events. If a standard battery-only solution were being sought, this would set the corresponding battery requirements versus the ICE filter time constant settings.

As seen in Figure 4, the required usable energy from the energy storage is approximately 1200 Wh regardless of the engine's filter time constant. The maximum energy requirement is determined by the two back-to-back city cycles. The energy required doesn't change dramatically for most cycles because the filter smoothes or averages the power profile, but does not significantly change the energy in the discharge power profile. The required energy illustrates that the ultracapacitors could not easily handle the energy requirement by themselves. Similarly, Figure 5 illustrates the energy storage power requirements versus the filter time constant setting for various cycles. The assist power requirement at the 10 s filter setting is 65 kW during the US06, which would result in a relatively high discharge current requirement of 200+ amps (at the nominal 300 V). Increasing the time constant toward 180 s results in assists approaching 100 kW or 300+ amps. Additionally, the maximum possible regenerative power remains very high (Table 3). Capturing the maximum regenerative power typically does not provide significant enough benefit to justify this sizing strategy alone. Moreover, increasing the filtering time constant too far may not be practical. However, fairly significant energy storage power capability is still necessary to downsize the vehicle with even a relatively modest 10 s load averaging. This scenario presents the issue that faces battery solutions in modern hybrids: energy capability is often adequate, but the engine cannot be significantly downsized without substantially increasing stresses on the battery caused by power requirements. An alternative approach has been to increase the battery pack voltage by using more modules. However, this results in more challenging packaging, reliability, and cost concerns. Overall, this problem is strikingly similar to the engine downsizing issue: Highly transient, short duration loads require the battery pack to be sized much larger than average power requirements would dictate. With a hybrid energy storage pack, the next step in load averaging the power profile (battery filter time constants) is studied for this issue.

4.2 Evaluating the Load Averaging Capability for the Battery Pack

The battery and ultracapacitor requirements should be evaluated for each level of ICE filter settings. Assuming the engine has been downsized to 60 kW, the load averaging time constant for the engine will be varied from 10 s upward. At a specified ICE filter setting, additional parametric sweeps are performed for battery load averaging. Similar to the ICE analysis, these sweeps lead to peak and average powers and total energy needed from both the battery pack and ultracapacitor bank. First the power requirements as a function of filter settings will be examined for the battery and then the ultracapacitor. Then, the energy requirements as a function of filter settings will be examined for the battery and ultracapacitor packs.

4.2.1 Peak Battery Power Requirements versus Filter Settings

The peak battery power requirement varies with both ICE filter setting and battery filter setting. The limiting case occurs during the US06 cycle (see Figure 6). The fc_{tx} notation in Figure 6 and subsequent figures is from the ADVISOR notation of **f**uel **c**onverter for the ICE. The tx subscript refers to the filter time constant setting. The family of lines represents the ICE filter parameters. Larger ICE filter time constants result in greater ICE load averaging, and thus, larger battery power requirements. This is a direct result of the transients being shifted from the ICE to the battery. Likewise, the battery power requirements increase exponentially as the battery filter time constant is reduced toward the [imposed] minimum of 0.5 s. In this case, the transient responsibilities are being shifted from the ultracapacitor to the battery. At the 0.5-s battery time constant setting, the battery power requirements are about 60–95 kW depending on the ICE filter setting, resulting in discharge current levels that are essentially above realizable current levels in a single series-configured pack. Hence, the US06 battery power requirements can result in cases where the battery and ICE filter setting combinations should be avoided (and in contrast, regions where they would be desirable), but by itself the US06 does not give insight into where the filter settings should be.

By comparison, the city, highway, and grade tests all require ≤ 35 kW peak battery power for the most demanding filter settings. The other notable peak power requirement is during the maximum acceleration, which requires nearly 40 kW of energy storage assist for as long as 40 s (with the 60 kW ICE). Battery power of 38 kW is still pushing the envelope of achievable current, at about 125 amps, but the duration of this event results in the use of 330 Wh. This magnitude of energy could entirely drain an ultracapacitor bank during a single maximum rate acceleration, so will require the use of the battery. This requirement sets an upper bound for the peak battery power at about 38 kW.

4.2.2 Peak Ultracapacitor Power Requirements versus Filter Settings

The remaining aspect of the power requirements is how the ultracapacitor power profile changes versus the battery filter settings. As seen in Figure 7, The ICE filter parameter has virtually no effect on the ultracapacitor power requirements since the family of lines are on top of one another. However, as the battery filter time constant is decreased to the 0.5 s [imposed] minimum setting, the peak ultracapacitor power requirement decreases from 100 kW to 50 kW. For ultracapacitors, the currents at 100 kW power levels from the 400 V maximum operating voltage down to the minimum operating voltage of 200 V are 250–500 amps. This amperage would require massive cables and exceeds some smaller ultracapacitor operating currents, but is still conceivable with some larger cells. More likely, though, faster battery filter time constants would be chosen to enable the ultracapacitor to handle lower currents. As mentioned earlier, sizing the energy storage to accept all the regenerative power events, such as the 150-kW events during the US06, is not usually practical.

The city, highway, and grade tests all result in assist and regenerative peak power events that are <50 kW for the most demanding (with respect to ultracapacitor operation) filter settings.

4.2.3 Peak Battery and Ultracapacitor Energy Requirements versus Filter Settings

At this point, from the energy storage perspective, only peak battery and ultracapacitor currents could help dictate one set of filters versus another. Evaluating the energy storage curves helps to provide better insight into the sizing trade-offs.

By integrating the cumulative power required from the pack during the drive cycle, we obtain the US06 battery and ultracapacitor energy requirements in Figure 8 and Figure 9, respectively. In this case, the battery system needs to provide more energy as the ICE filter setting is shortened. This is because the ICE responds more quickly to the assist transients, which results in less alternating assist and regenerative energy through the battery and more net regenerative events into the battery. Also, as the battery filter parameter is shortened, the required battery energy increases because the battery is accepting a higher percentage of the transient pulses and performing less load averaging. Nonetheless, the energy ranges required during this cycle are relatively low compared to energy available in battery packs.

Alternatively, the required ultracapacitor energy decreases as the battery transient response quickens (see Figure 9). For longer battery response times, relatively large, yet still attainable, ultracapacitor energy capacity is required. A relatively short battery response time supports keeping the ultracapacitor energy requirements down. Thus, both ultracapacitor energy and power requirements are minimized with shorter battery response times. The ultracapacitor energy required during the US06 (Figure 9) represents the peak energy requirement over all the drive cycle power profiles examined.

The longer city cycle dictates the peak battery energy requirement (Figure 10). The trends are similar to the US06 trends, but energy requirements peak at 1260 Wh toward the end of the 45+ min cycle. Additionally, the maximum acceleration cycle could require 330 Wh to maximum speed (Figure 4). A more likely 0–85 mph acceleration event would contain a peak 38 kW energy storage power assist for approximately 21 s. Each 0–85 event would require about 220 Wh of energy from the energy storage. However, the ultracapacitor could be used to reduce that peak battery power requirement by supporting a percentage of the power assist during peak acceleration events.

5. Making Trade-Offs in Sizing Hybrid Systems

From the perspective of ICE sizing, load averaging above the 10-s averaging time provides no ICE downsizing advantage because continuous grade requirements dictate a minimum engine size. In selecting the ICE filter time constant, further consideration should be given to throttle transient effects on system efficiency and emissions, and gear selection for maximum efficiency operation. The ICE filter time constant parameter has less effect on battery and ultracapacitor peak power sizing, since the battery filter time constant can be quite flexibly adjusted to vary the required battery and ultracapacitor powers. However, the ICE filter time constant does affect the battery and ultracapacitor energy requirement more significantly. Since the FIR averaging filter doesn’t contain a means to control energy storage SOC, the ICE filter setting’s influence on the energy storage energy requirement might be mitigated through active SOC set point management. At the very least ICE downsizing will require a minimum energy storage capacity to support multiple maximum acceleration events.

The battery could be downsized to substantially lower peak power requirements; however, the downsized ICE requires some energy storage assist during the maximum acceleration events. If used alone, ultracapacitors don't have enough energy to sustain more than one maximum acceleration event, so the battery peak power should be sized to support the bulk of the energy storage assist during these events. However, allowing the ultracapacitor to provide a percentage of the maximum acceleration power assist can allow the battery peak power requirement to be further relaxed so the battery can be stressed less and possibly downsized further. As the battery time constant is relaxed (more load averaging), the battery energy requirement typically decrease as well. However, the ultracapacitor peak power and energy requirements increase as battery time constant increases. Thus, the battery limitations and advantages versus the ultracapacitor limitations and advantages must be evaluated for each pair of feasible filter settings to balance the two systems roles.

To illustrate the possible profiles from a hybrid system, we will show an example of a system with a 60 kW ICE with a filter time constant of 20 s; a 30 kW (current limited, so that power is limited to 30 kW), 1800 Wh (usable) battery system with a filter time constant of 10 s; and a 50–100 kW (at $V_{minimum}*I_{maximum}$ and $V_{maximum}*I_{maximum}$, respectively), 94 Wh (usable) (900 F/cell) ultracapacitor system. The battery is sized at 1800 Wh so that it will provide 1440 Wh at end-of-life (80% capacity remaining). Maxwell typically specifies it ultracapacitors' capacitance after the "break-in" period, so no end-of-life adjustment was made for ultracapacitor capacity. Example systems would be the 12 Ah Saft Lithium cell (6 Ah usable, 4.8 Ah usable at end-of-life), and the 900 F Maxwell Boostcap (94 Wh usable) [11, 12]. The filter time constant was chosen based on limiting the battery current to a maximum capability of <100 amps – which should only be required during the maximum effort acceleration events. After setting the maximum power limit to 30 kW, ICE and battery time constants were chosen from Figure 6 so that the peak power during the US06 would be lower than the 30 kW maximum power. At the 20 and 10 s time settings, the maximum power required from the battery during the US06 (and by default, the other cycles) should be approximately 23 kW. From choosing a set of filter time constants, the required battery and ultracapacitor energies are then set according to the maximum energy needed for a cycle, which is the city cycle for the battery (~1255 Wh) (Figure 10) and the US06 cycle for the ultracapacitors (~65 Wh) (Figure 9). Additionally, these energy values are compared to those required by multiple 0–85 mph maximum acceleration events. Two back-to-back 0–85 mph events (assuming no regenerative energy) were used in this case, resulting in a 350 Wh battery requirement (30 kW for 21 s, 2 times) and a 94 Wh ultracapacitor requirement (8 kW for 21 s, 2 times). Four 0–85 mph acceleration requirements could be imposed without changing the battery, but the ultracapacitor would need to be increased to 1800 F/cell. However, this ultracapacitor cell has a higher current capability so could provide more transient power capability [13]. Figure 11 shows the component power responses during the US06 cycle. The power integration for the total energy storage, battery, and ultracapacitor systems during the US06 cycle can be seen in Figure 12.

6. Conclusions; Future Work

Using multiple power sources allows for optimizing the uses of each power plant based on its unique characteristics. While single power plant vehicles must be designed for peak transient as well as average loads, hybrid power plant and hybrid energy storage solutions allow for the possibility of load segregation based on the strengths of each component. This paper explored various drive cycle power profiles using an anti-causal, zero-phase digital FIR averaging filter to divide component roles into load averaged segments. The non-causal filter would need filtering modifications and other component-based considerations to apply to a real-time control system. The aim of this work was to explore whether hybrid energy storage packs could be sized, in conjunction with the ICE, to result in downsized, more specialized, component sets that, when working together, meet all the average and transient loads required in vehicle operation. Through the analyses, we discovered that increasing the ICE time constant beyond a 10 s load-averaged setting had no additional impact on downsizing the engine due to the requirement to sustain a set speed at maximum grade. Furthermore, with a downsized engine, the energy storage system will need sufficient energy to sustain power assist during maximum acceleration events. Thus, the battery power will need to meet (for battery-only energy storage) or be very close to (for a hybrid battery and ultracapacitor energy storage) the remaining maximum acceleration power requirements. The total energy storage energy requirement is strongly dependent on the regenerative energy recoverable because the filtered engine power's cycle energy content is largely unchanged as the filter time constant changes. Overall, this approach should help to alleviate stresses on components, particularly the battery component. Eliminating battery stresses can lead to improved thermal, electrochemical balancing, and aging scenarios. This paper does not intend to conclude which level of load averaging will result in an optimized hybrid system.

Future work based on load averaging developments should lead to (1) implementing load averaging in a real-time control system with real-world requirements taken into account, such as SOC control and gear selection for maximum engine operating efficiency, and (2) using optimization to adjust filter time constant settings and component sizing to obtain maximum fuel economy, minimum mass, and minimum volume. ADVISOR™ has been used extensively for efficiently running optimization routines to explore and optimize fuel economy, emissions, mass, and volume scenarios for hybrid electric vehicles.

7. Equations

$$E_{battery} = Ah_{Usable\ Capacity} * V_{nominal} \qquad [Wh] \qquad (1)$$

$$E_{capacitor} = \tfrac{1}{2} * (C_{cell} / \#_{cells})(V_{max}^{2} - V_{min}^{2}) * (1/3600) \qquad [Wh] \qquad (2)$$

8. Figures and Tables

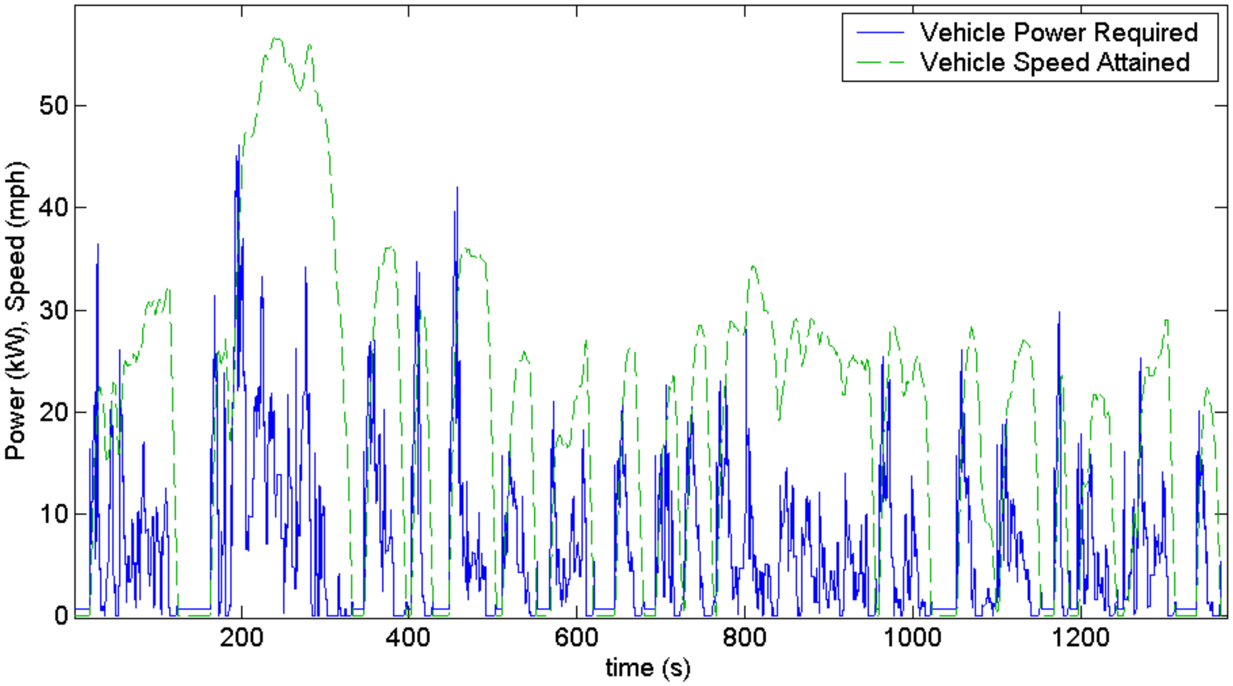

Figure 1: Power profile for the mid-size car over the UDDS cycle

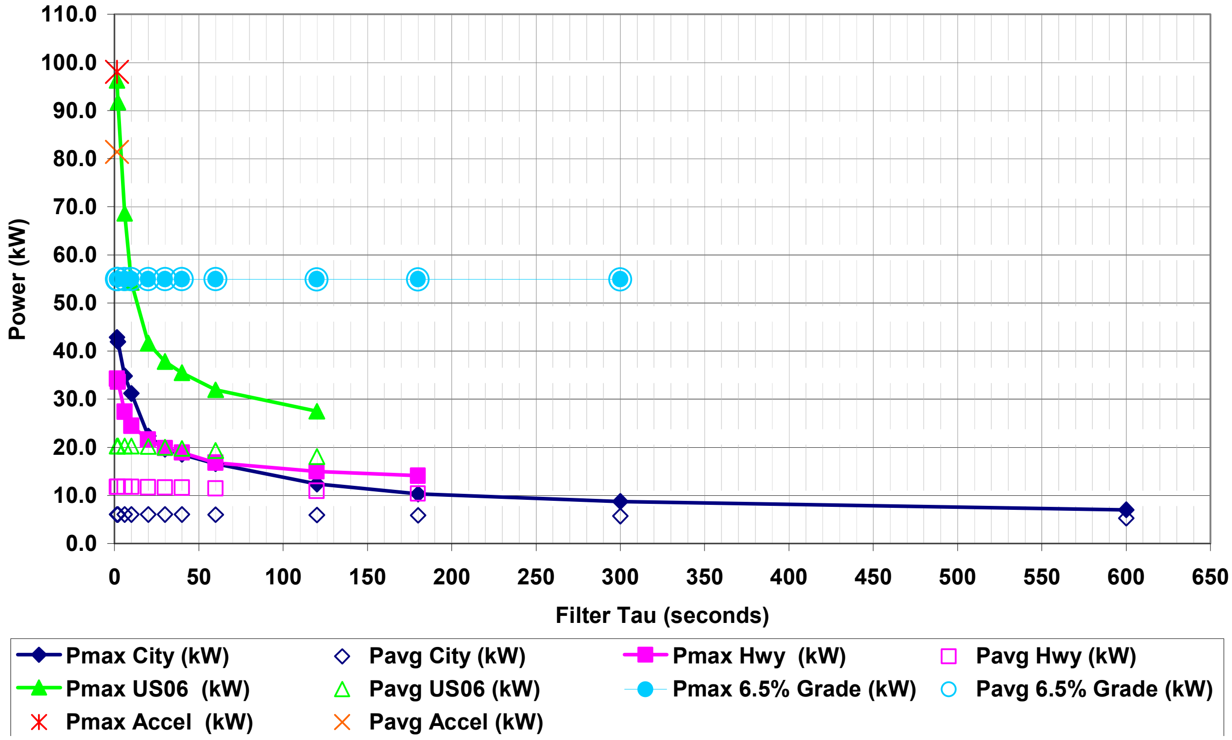

Figure 2: ICE output power versus ICE filter time constant settings

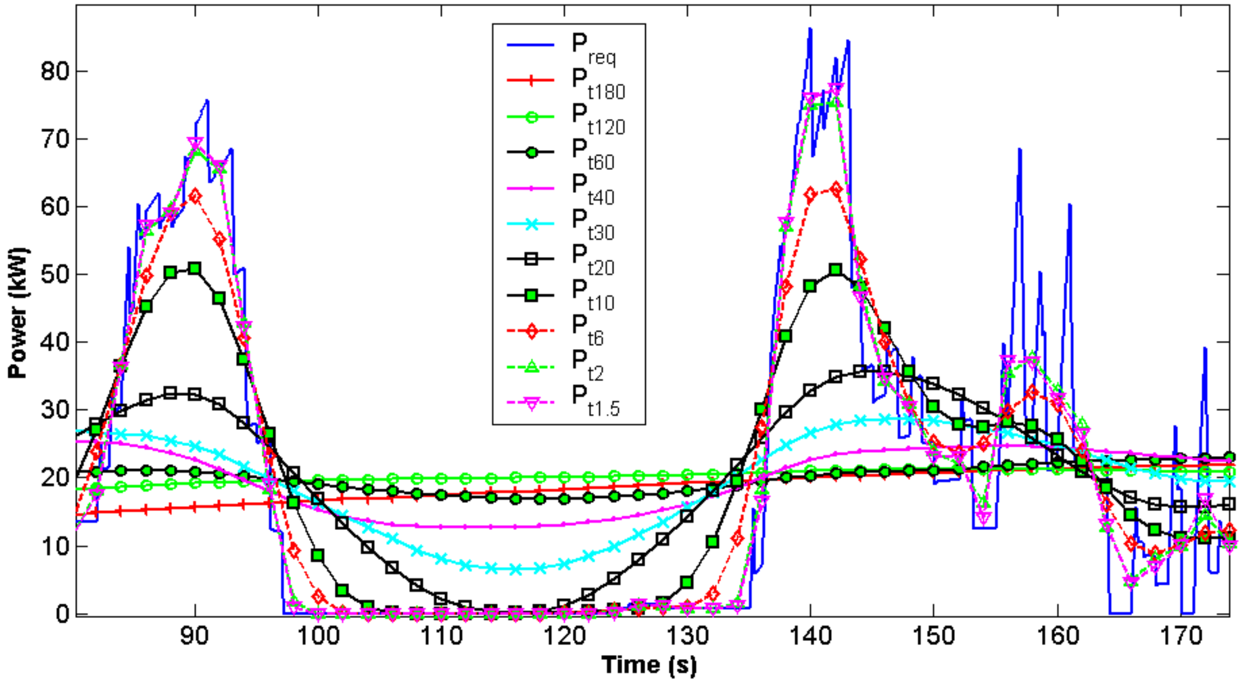

Figure 3: Example ICE power response for various power set point filter settings during part of the US06 cycle

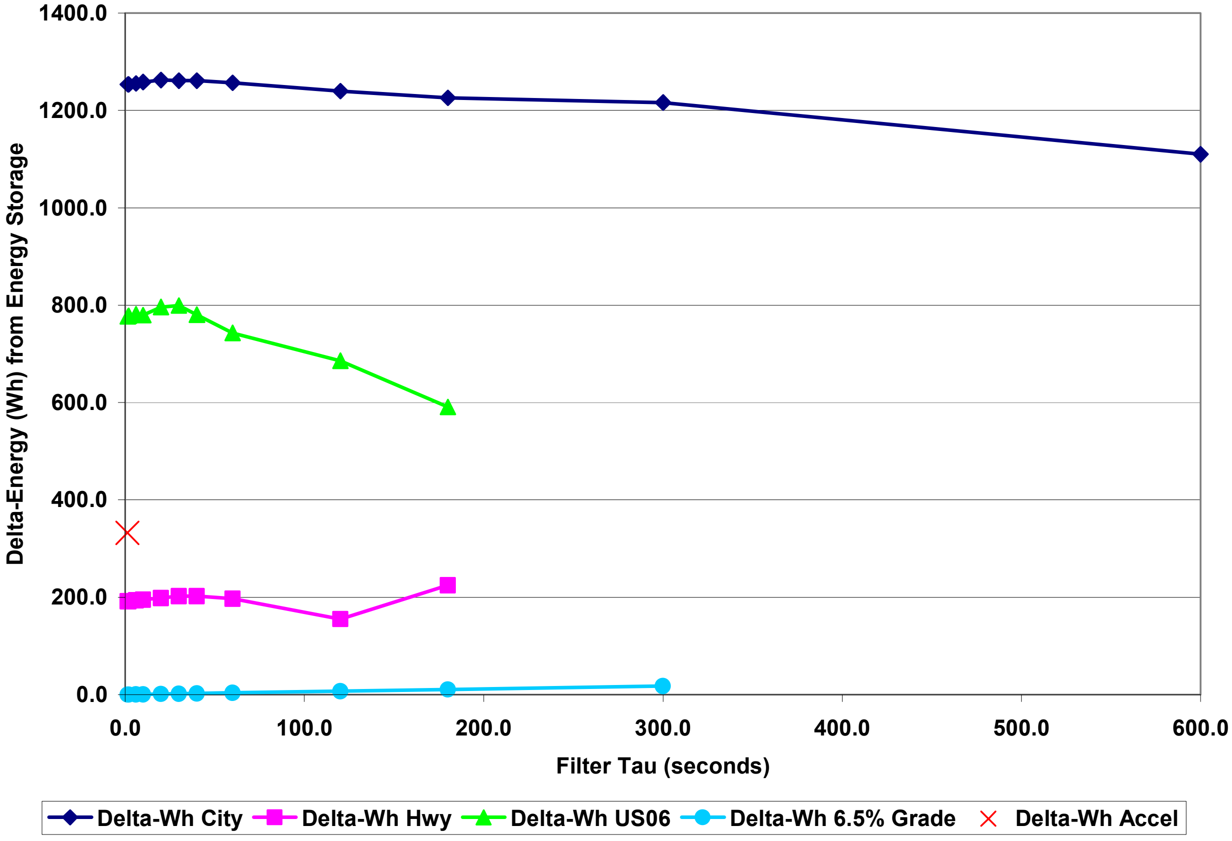

Figure 4: Energy storage Wh capability needed versus set points for implementing load averaged engine operation

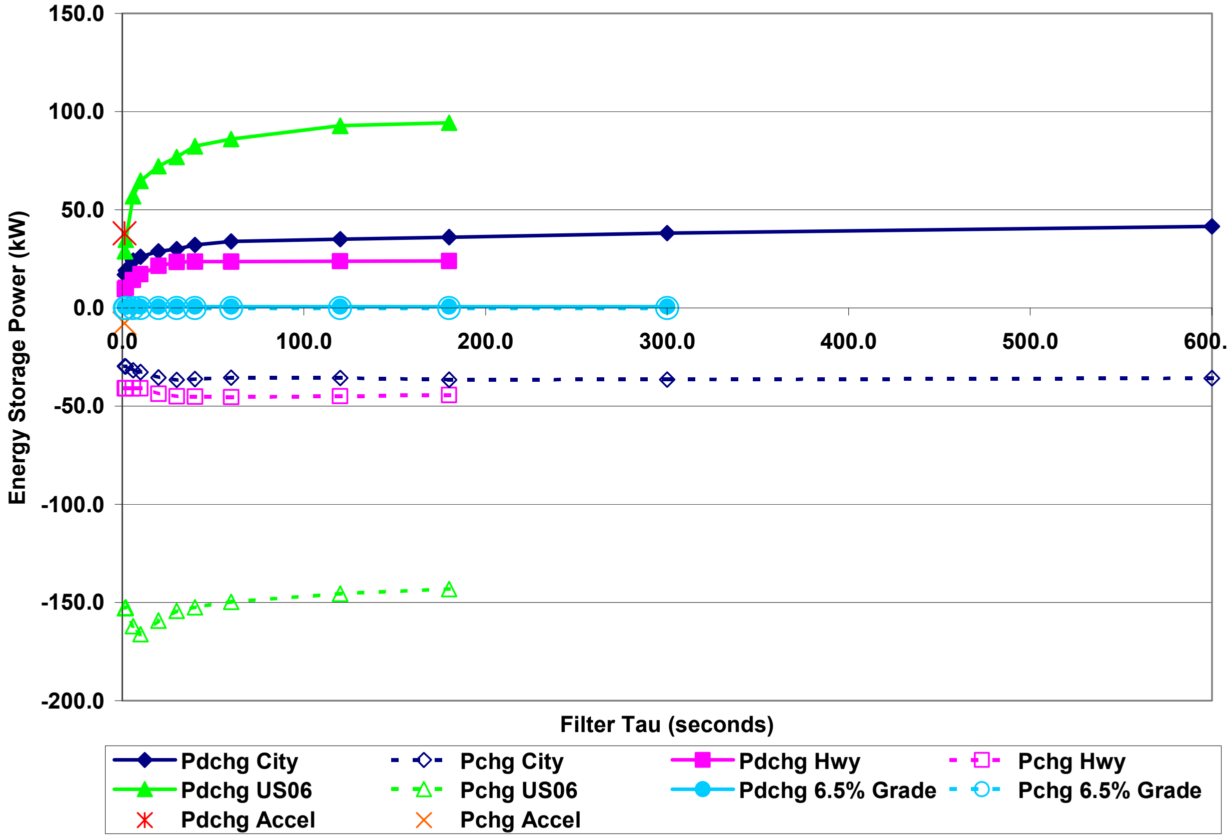

Figure 5: Energy storage power capability needed versus set points for implementing load-averaged engine operation

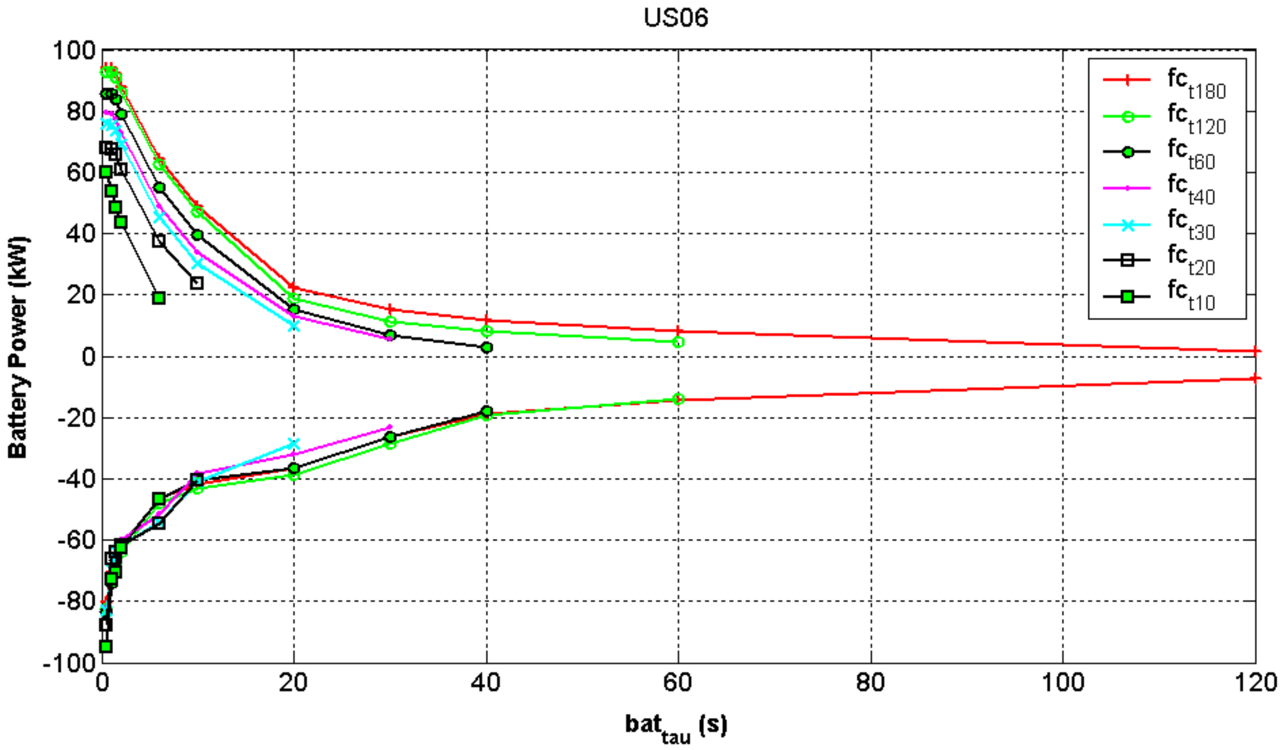

Figure 6: Battery power requirements during the US06 versus battery time constant setting with lines for ICE time constant setting (The fc$_{tx}$ notation is for **f**uel **c**onverter [the ICE] time constant setting)

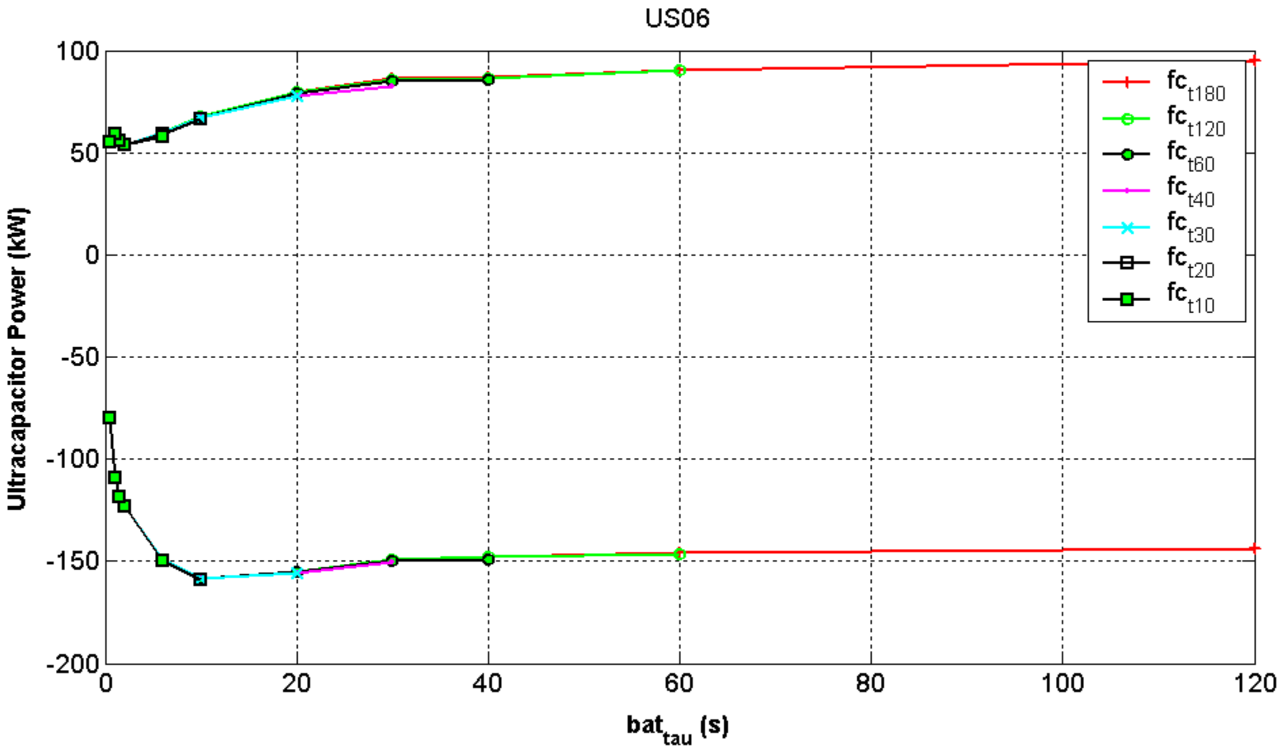

Figure 7: Ultracapacitor power requirements during the US06 versus battery time constant setting with lines for ICE time constant setting

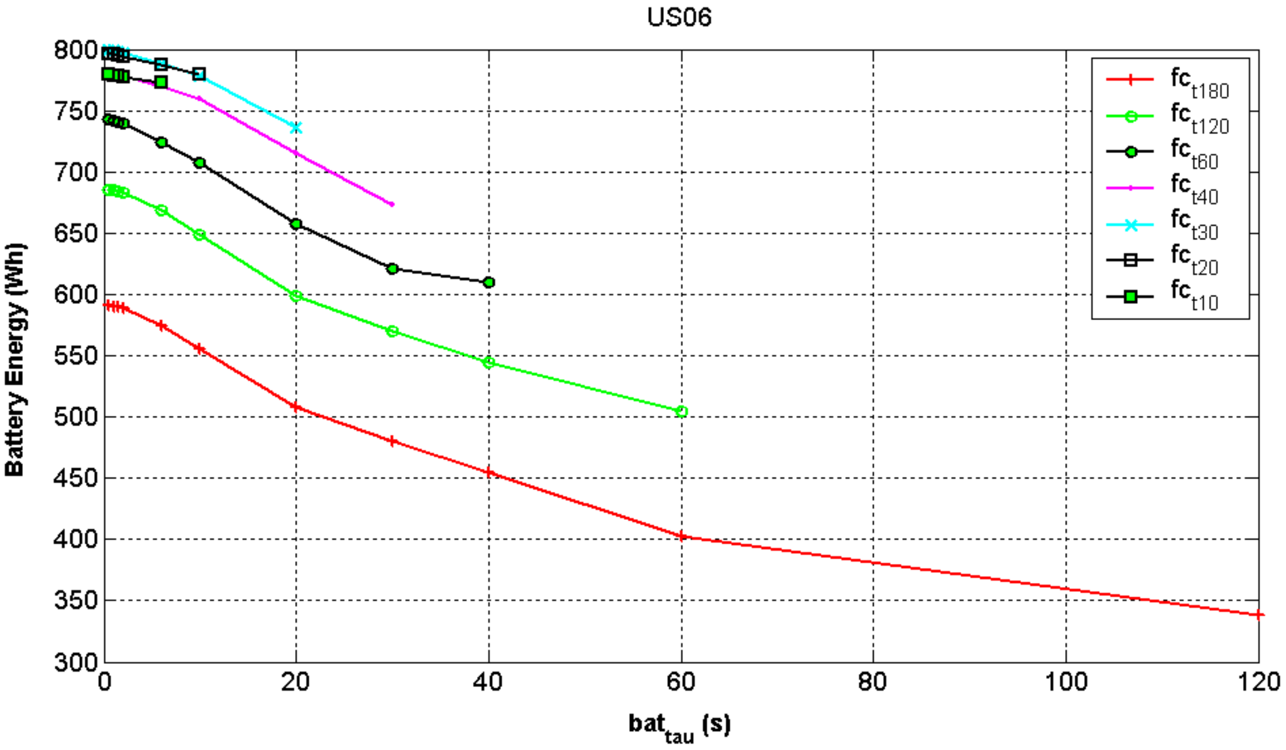

Figure 8: Battery energy requirements during the US06 cycle versus battery time constant setting with lines for ICE time constant setting

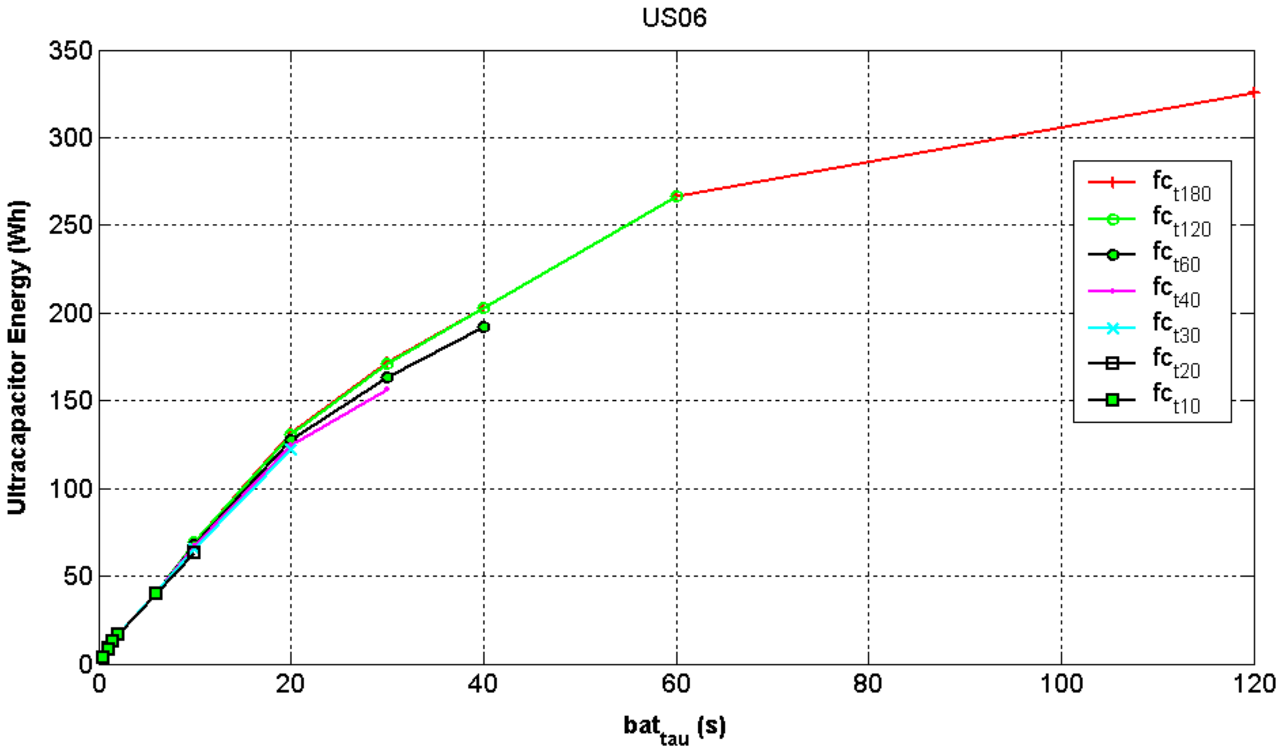

Figure 9: Ultracapacitor energy requirements during the city cycle versus battery time constant setting with lines for ICE time constant setting

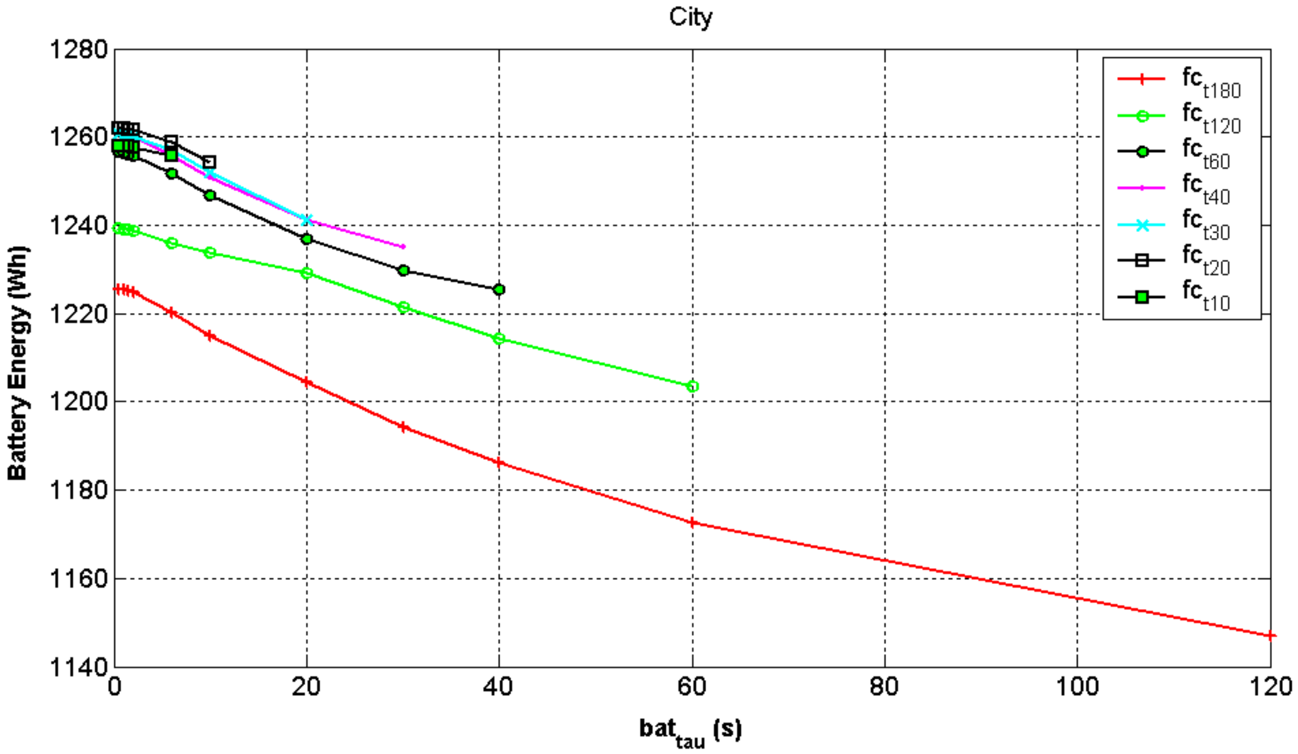

Figure 10: Battery energy requirements during the city cycle versus battery time constant setting with lines for ICE time constant setting

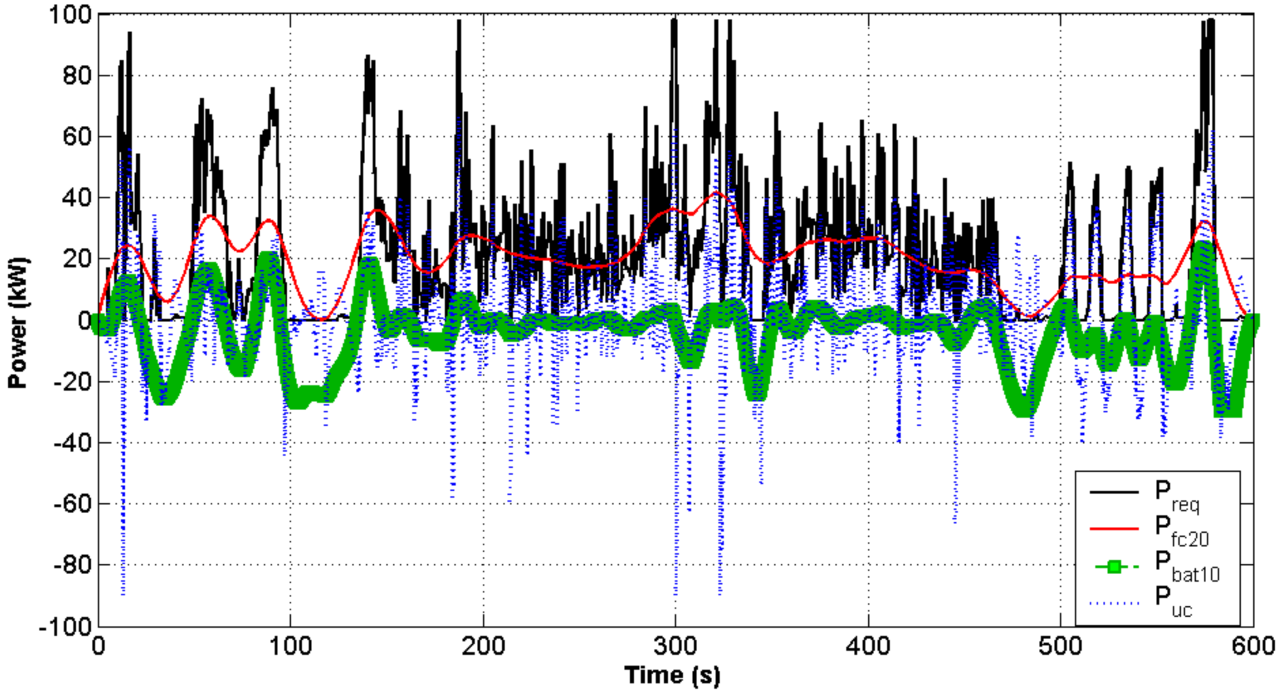

Figure 11: Total power required and power distribution between the ICE, battery pack and ultracapacitor pack during the US06 cycle

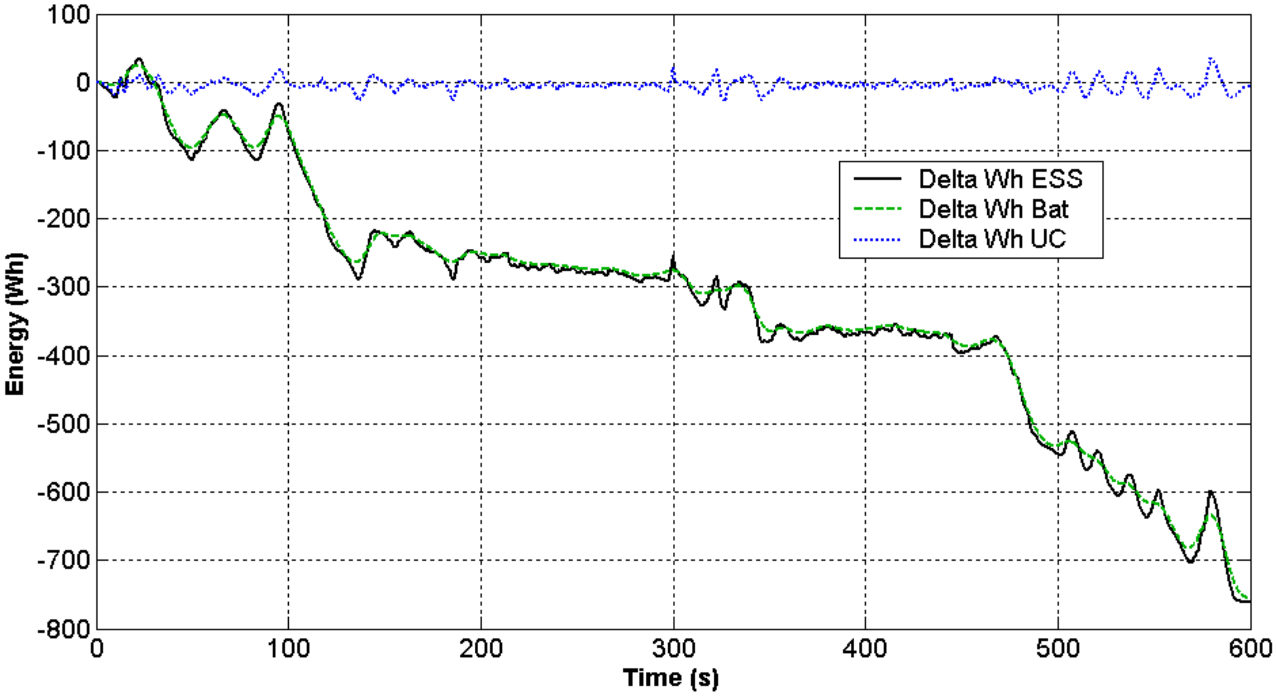

Figure 12: Total change in energy required and energy distribution between the battery pack and ultracapacitor pack during the US06 cycle

Table 1: Vehicle assumptions

Assumption Description	Units	mid-size Car
Vehicle Description	--	Front wheel drive mid-size car
Base Conventional Vehicle Mass	*kg*	1513
Base Vehicle Glider Mass	*kg*	1014
Base Conventional Powertrain Mass	*kg*	499
Cargo Mass	*kg*	136
Aero. Drag Coef.	--	0.33
Frontal Area	*m^2*	2
Vehicle Range	*mi*	320
Powertrain Available Volume	L	435

Table 2: Performance assumptions

Assumption Description	Units	mid-size Car
0-60 mph	*s*	10.9
Top Speed	*mph*	100
Grade @ 65mph for 20min. at Curb Mass + 408kg	*%*	>=6.5
Drive Cycle Tolerance	*mph*	<=2
SOC Balancing	*%*	<=0.5%

Table 3: Total assist and regenerative power required in peak demands and average demand for various drive cycles

	Units	US06	Hwy	UDDS	6.5% Grade	Max Accel
P_{max_req}	*kW*	98.0	36.6	46.2	54.9	98.0
P_{avg_req}	*kW*	20.3	11.8	6.0	54.9	81.4
P_{maxrgn_req}	*kW*	159.8	40.9	29.2	0.0	0.0
P_{avgrgn_req}	*kW*	4.6	0.9	1.6	0.0	0.0

Table 4: Example range of usable energy for a range batteries or ultracapacitors configured in a 300 V pack

	Battery Capacity (Ah)	Usable Battery Energy (Wh)	Ultra-capacitor Capacitance (F)	Usable Ultra-capacitor Energy (Wh)
Lower Bound	*5*	750	500	52
Upper Bound	*50*	7500	5000	520

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10. Authors

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