
The Electrification of the Automobile: From Conventional Hybrid, to Plug-in Hybrids, to Extended-Range Electric Vehicles

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ABSTRACT

A key element of General Motors' Advanced Propulsion Technology Strategy is the electrification of the automobile. The objectives of this strategy are reduced fuel consumption, reduced emissions and increased energy security/diversification. The introduction of hybrid vehicles was one of the first steps as a result of this strategy. To determine future opportunities and direction, an extensive study was completed to better understand the ability of Plug-in Hybrid Electric Vehicles (PHEV) and Extended-Range Electric Vehicles (E-REV) to address societal challenges. The study evaluated real world representative driving datasets to understand actual vehicle usage. Vehicle simulations were conducted to evaluate the merits of PHEV and E-REV configurations.

As derivatives of conventional full hybrids, PHEVs have the potential to deliver a significant reduction in petroleum usage. However, the fuel consumption benefits are limited by the underlying constraints of the base hybrid systems and vehicles. Even with incremental electric power and speed improvements, the PHEV's lack of full-performance, all-electric capability requires engine operation under everyday speed and/or load conditions, regardless of available battery energy. This creates emissions concerns and can severely limit the actual all-electric driving range in the real world.

The E-REV is principally an Electric Vehicle (EV) with full vehicle performance available as an EV. Significantly, it overcomes the historical EV re-charge time limitations by adding a fuel-powered electric generator to extend driving range. Actual all-electric driving can regularly be experienced throughout the working energy range of the vehicle's battery without fear of being stranded. The E-REV offers the opportunity for petroleum independence, and a dramatic reduction in emissions for many drivers.

An E-REV traction drive and battery system needs to be specifically designed for the task. The systems are significantly more capable and larger than those designed for PHEVs. An E-REV is typically also architected to accommodate packaging of these systems while retaining performance and utility. The compelling benefits of the E-REV drive GM to address these challenges.

The study results indicate that both the PHEVs and the E-REVs can play a role in addressing future needs. The study shows that in the real world the PHEV is quite likely to run with blended operation, but the E-REV is very likely to remain in EV mode for most drivers.

GM is currently developing both PHEV and E-REV vehicles. The Saturn VUE Green Line PHEV is being developed as a derivative of the conventional 2-Mode Hybrid. The Chevrolet Volt E-REV is also under development with full performance, all-electric capability, but without practical range limitations.

INTRODUCTION

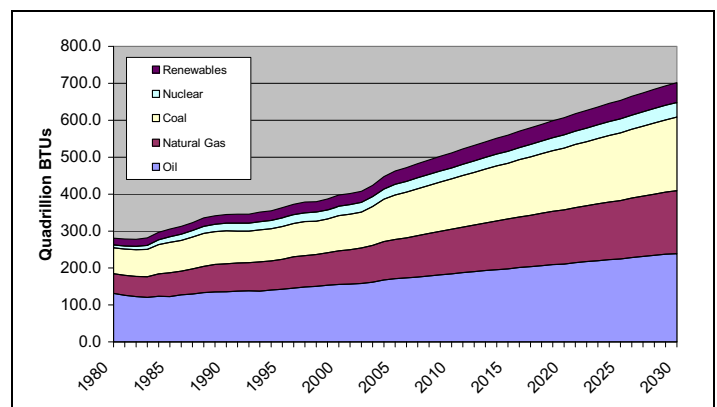


Figure 1 – Projected worldwide energy sources

ENERGY OUTLOOK - Worldwide energy production is projected to grow at an annual rate of over 2% providing

for an expanding population and industrial development, despite increasing efficiencies in consumption. Figure 1 shows that fuels, primarily petroleum oil is projected to grow at a similar rate, even in scenarios where the fuel remains at relatively high historical costs. 2030 World oil consumption is accordingly projected at 210 quadrillion Btu (118 million barrels annually), an increase of over 30% compared to 2004. The portion of oil used for transportation is growing and is projected to use 68% of liquid fuel energy over the period 2004 - 2030. [1]

Significant concerns have been raised about the security of oil supply and initiatives have been outlined to diversify energy in transportation including initiatives proposed by the US Administration and the Department of Energy [2]. These initiatives include the development of a vehicle that plugs-in and derives a great deal of its utility using energy from the electric power grid. Recent enthusiasm in PHEVs and E-REVs, in part, stems from these concerns.

General Motors' Advanced Propulsion Technology Strategy is to remove automobiles from the environmental dialogue. The strategy calls for reduced consumption, reduced emissions, and diversification of energy sources. Continued improvements in base vehicle and powertrain efficiencies figure prominently in GM's plans, as does an aggressive rollout of ethanol-blended fuels.

Another key element of the strategy is to allow automobiles to shift significant portions of their required energy from petroleum to other sources. Figure 2 shows a network of the various energy sources, energy pathways, and possible on-vehicle energy storage media. Higher power motors, higher energy on-board electrical storage, and systems that allow for driving without a combustion engine enable vehicles that can use non-petroleum energy sources for transportation. We call the increase in electrical content and magnitude onto the vehicle "electrification".

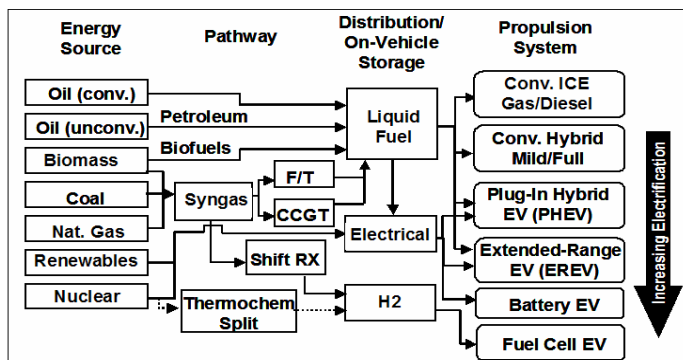


Figure 2 – Energy sources, paths, on-vehicle storage and vehicle propulsion systems

Diverse energy sources figure into the future of the world's total energy bill. Yet today, automobiles rely

almost exclusively on liquid fuels as the on-vehicle storage medium. Note that most other sources can be, and are already, used as part of the electric grid as shown Figure 3.

Electric grid power is a natural candidate for transportation energy distribution with on-vehicle storage. Worldwide grid electricity is expected to approximately double in the next two decades, outstripping the growth in total energy consumption. Improved generating efficiency from new plants means that electrical generation will continue to use approximately 40% of the world energy sources [1].

If electric energy can be effectively stored and integrated to propel automobiles, the full range of energy sources could be tapped for future automotive needs. Furthermore, future improvements in the efficiency and environmental impact of electric power generation will be directly realized by the PHEVs and E-REVs on the road at that time.

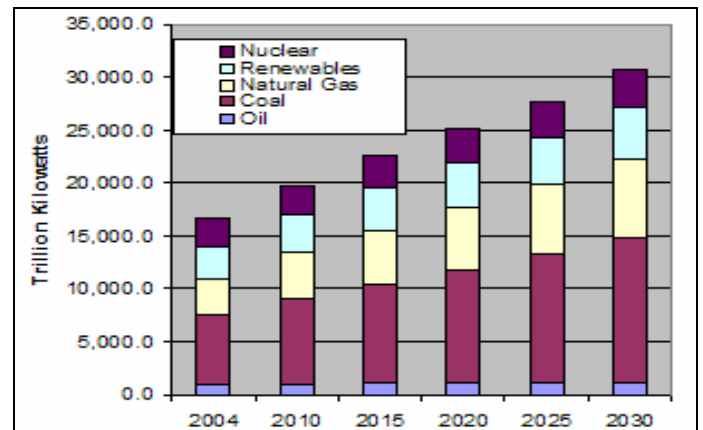


Figure 3 – Projected worldwide electric power capacity

ELECTRIFICATION - Several technical and commercial challenges are associated with charging, storing and making use of electric energy to propel automobiles. The term "electrification" means development and integration of systems and components that enable electric energy to be used for transportation. Challenges of electrification include providing automotive levels of reliability and durability, package density, acceptable noise, vibration and harshness, and automotive levels of cost in a set of new components and control algorithms.

Electrification has its roots in modern times with introduction of the first modern electric vehicle, the 1996 GM EV1. The EV1 was a full performance Battery Electric Vehicle (BEV) with a complete set of vehicle electrification technologies [3]. They included the first modern:

- Vehicle charging interface

- Off-board charging system
- Battery pack and charge control system
- Electric isolation system
- Electric drive and traction system
- Electric accessory power system
- Electric steering system
- Electric air conditioning system
- Electrically actuated brakes
- Regenerative braking systems

The EV1 also included an efficient vehicle package and structure designed at the outset to accommodate a battery pack with sufficient energy and power for full performance as an electric vehicle.

Unfortunately, the market experience with the EV1 indicated that additional improvements in BEVs were needed. Some EV1 drivers gave the term “range anxiety” to their continual concern and fear of becoming stranded with a discharged battery in a limited range vehicle. Improvements in on-board energy storage and charging time were necessary for more widespread deployment of BEVs. Most EV-enabling electric components and systems have found utility in the meanwhile when used in mild and full Hybrids Electric Vehicles (HEVs).

TRANSITIONAL ELECTRIC VEHICLES - Electrification has continued in the industry with the development of conventional HEVs. These vehicles do not provide full performance on electric power alone, and therefore the power and energy level required for the systems is reduced when compared with full performance BEVs. In addition, while conventional hybrids (both mild and full) improve vehicle efficiency and directly reduce petroleum consumption and CO₂ emissions, all the energy they consume is from an on-board liquid medium. In HEVs, electric storage and power on board are only used to better utilize the liquid fuel. Therefore, HEVs offer no additional energy pathways for diverse sources, including CO₂ neutral renewables.

However, hybrids are being produced at volumes now sufficient to develop and improve the reliability and cost effectiveness of electrification subsystems. Considering a long-term goal of greater energy diversification, hybrids can be considered the first of transitional electric vehicles. Figure 4 is a table illustrating the features of transitional electric vehicle types, including HEVs, Plug-In Hybrid Electric Vehicles (PHEVs) and Extended-Range Electric Vehicles (E-REVs). Each is progressively more electrified and we expect plays a progressively larger role toward shifting a portion of the transportation energy burden toward other sources and away from petroleum.

Vehicle Type	Electric Power	Onboard Electric Storage	Grid Conn.	Electric Driving
Mild HEV	low	low	no	no
Full HEV	med	low	no	very limited
PHEV	med	med	yes	limited
E-REV	high	high	yes	Full

Figure 4 - Features of Transitional Electric Vehicles

MAIN SECTION

DEFINITIONS – Before beginning a detailed discussion on the benefits of varying degrees of electrification it is necessary to define the key systems.

Hybrid - A hybrid is defined by SAE [4] as: “A vehicle with two or more energy storage systems both of which must provide propulsion power – either together or independently.” In practice, hybrid vehicles typically require both sources to provide full vehicle capability. The engine is also typically the larger of the two propulsion sources, being sized to provide most of the power during high power vehicle events. The motor is typically the smaller of the two propulsion sources, being sized to maximize the amount of energy that can be captured during braking and for limited low speed EV operation.

Plug-in Hybrid (PHEV) - A PHEV has been defined by SAE [4] as: “A hybrid vehicle with the ability to store and use off-board electrical energy in the RESS (rechargeable energy storage system).” These systems are in effect an incremental improvement over the Hybrid with the addition of a large battery with greater energy storage capability, a charger, and modified controls for battery energy management and utilization.

There are two types of PHEVs operating strategies. These operating strategies require the definition of a schedule for discussion. The EPA urban, referred to as the urban, schedule is a common reference for PHEVs and will be used for this discussion.

The first type has an operating strategy which is very similar to the conventional hybrid. The engine use is required for most accelerations and speeds. The characteristics of this mode of operation are shown in Figure 5. Here you can see that the engine starts almost from the start and engine power is used throughout driving to supplement battery power usage. For PHEVs that use conventional hybrids as the starting point, this mode of operation is typical due to the operational speed and electrical power capabilities of the underlying hybrid systems. We call such a hybrid a conversion PHEV.

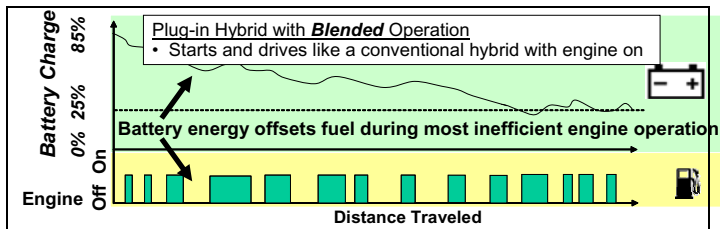


Figure 5 – A Conversion PHEV using a blended operating strategy

The second type of PHEV operation strategy is referred to as *Initial EV*. This type of system requires that the battery, motors, thermal systems, power electronics and system configuration be set to allow electric-only operation over the complete power and speed range of a cycle, in this case the urban schedule. The characteristics of this mode of operation are shown in Figure 6. In this figure you see that while the battery is depleting the stored energy the vehicle operates electric-only, without any engine operation. Once the battery is depleted, the vehicle operates like a conventional hybrid.

In real world operation, anytime during operation that the driver requests more power or speed than the motor and battery can provide, the engine is required to start and the controls will default to a *Blended* mode of operation to maintain emissions capability. In order to delay engine start in an Initial EV PHEV, a full hybrid system may have to be additionally modified to raise the traction power capability, and to extend the speed at which the vehicle operates electrically. We will examine the benefits of such modifications sufficient to drive the urban driving schedule, and call it an “urban-capable PHEV”.

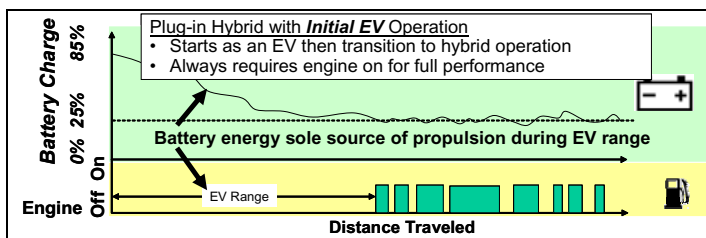


Figure 6 – A Urban-Capable PHEV using an Initial EV operating strategy

Extended-Range Electric Vehicle (E-REV) - SAE has not established a definition for an E-REV. The authors propose the following definition: “A vehicle that functions as a full-performance battery electric vehicle when energy is available from an onboard RESS and having an auxiliary energy supply that is only engaged when the RESS energy is not available.” This is very similar to a vehicle envisioned in the 2007 ARB Expert panel report [5], when they described,

“This type of vehicle can operate as a full performance ZEV, during the time the ICE is not operating, and can avoid the cold start emission

problem discussed above and it requires a relatively large energy battery and a large full performance, electric drive propulsions system, similar to FPBEV or FCEV....”

The E-REV is unique from a PHEV in that the vehicle, battery and propulsion system are sized such that the engine never is required for operation of the vehicle when energy is available from the battery. The definition of this type of vehicle does not require the specification of a operating cycle (urban schedule in the PHEV discussion). As a full-performance battery electric vehicle, the battery, motor, and power electronics must be sized for the full capability of the vehicle. The vehicle must also be architected to allow packaging of the large E-REV battery which has a greater size due to the full EV requirement. The characteristics an E-REV are shown Figure 7. The operation of an E-REV looks similar to that of an Initial EV PHEV; however an E-REV must maintain this mode of operation on all operating schedules when energy is available from the battery. An E-REV does not need to start the engine for speed or power demands from the driver and therefore does not need to transition to a *Blended* operation strategy when battery energy is available, unlike the *Initial EV* PHEV.

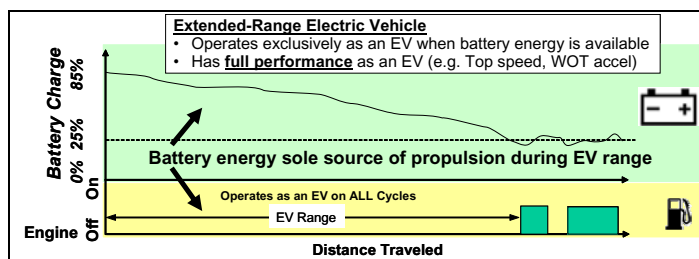


Figure 7–Characteristics of E-REV operation

A better understanding of the different systems is gained by examining Figures 8. This figure shows that as greater electric-only operation is required, there is a need to increase motor size and overall electric propulsion capability. Hybrid and PHEVs are able to blend electric and engine power to propel the vehicle and therefore require less total onboard power than the E-REV. The E-REV requires full electric propulsion capability and as such, the additional power capability of the total onboard power exceeds what is required to propel the vehicle. The E-REV does allow significant engine downsizing in that the engine power is not required to meet peak vehicle power demands and can be sized to meet only continuous power demand.

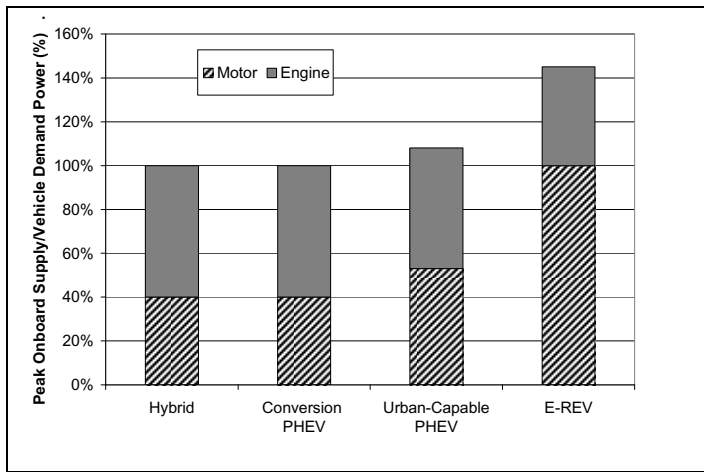


Figure 8 – Peak motor and engine power as a percentage of the peak vehicle power demand

ELECTRIC RANGE BENEFIT

There are three benefits to vehicle electrification: reduced petroleum consumption, reduced emissions, and energy diversification. Energy security comes from the ability to use multiple energy sources via electric pathways and on-vehicle storage, and a net reduction in fuel usage. Since energy security is so closely related to fuel usage reduction, we only consider fuel usage reduction in our study. To analytically evaluate these benefits three sources of data were used: the 2001 National Personal Transportation Survey, time series data from the Southern California Association of Governments (SCAG) Regional Travel Survey, and the Environmental Protection Agency’s (EPA) testing cycles.

Vehicle Usage & Powertrain Constraints Discussion

For E-REV’s and PHEV’s, there are three primary constraints that affect vehicle performance. Those constraints are the total energy stored in the batteries, battery power limits, and electric motor or mechanical speed limits. Any one of these limits can significantly reduce the system’s EV operation and subsequent opportunity to displace petroleum. At one extreme, the lowest level of performance for a PHEV is obtained by converting an existing HEV into a PHEV only by increasing on-board electrical energy storage and adding a charger, resulting in the conversion PHEV. This type of PHEV has blended-type operation and typically has speed, power, and energy constraints which cause the engine to start very soon after the vehicle moves. At the other extreme is the E-REV. An E-REV does not start the engine until all useable on-board electrical energy has been used. Between these two extremes are solutions which are able to operate like EVs to different degrees.

To evaluate the benefits of a non-conventional powertrain, the typical approach has been to consider the EPA’s testing cycles. These define a speed the vehicle must follow versus time during a test. Three of

the most commonly considered cycles are the urban, EPA highway, referred to as the highway cycle, and US06 test cycles. Using these cycles as a reference in designing powertrains naturally leads to systems which are designed to maximize performance against those cycles. One proposed level of PHEV performance is the ability to follow the urban and highway cycles while operating as an EV until the useable on-board electrical energy is exhausted. A transition from EV operation to Blended PHEV or HEV behavior occurs when either wheel power or wheel speed exceeds the level required to follow the urban cycle. This is the type of system previously defined as an ‘urban-capable PHEV.’

In addition to EPA cycles, other potential sources of design requirements exist. At a very high level, the National Personal Transportation Survey has information on travel times and distances. This information can provide insights into the potential fuel economy and emissions benefits of different PHEV and E-REV vehicle types. Additionally, some regions have collected detailed driving information on vehicle usage. The SCAG Regional Travel Survey (RTS) [6] is one example with data from the southern California area. With permission from SCAG, The National Renewable Energy Lab (NREL) released a copy of the RTS data set. The data was made anonymous by NREL to remove all personally identifiable information. It was reduced to 621 traces of speed versus time, and ignition key state versus time. Each trace corresponded to one vehicle instrumented in the RTS. In the raw form provided, the data set had problems with missing points. The data was processed to interpolate and fill in for missing data. The statistical characteristics of this data for distance and trip times are different than the NPTS data because it is a sub-sample of the population of vehicles from a specific geographic region.

One use of the RTS dataset is to evaluate vehicle power usage for ‘real-world’ drivers compared to existing federal driving schedules. To normalize the data to account for distance driven, the ‘power intensity’ for driving is calculated. Power intensity is defined as energy used by a vehicle divided by distance driven. Figure 9 shows the power intensity of each sample vehicle and the daily distance driven. Comparing the RTS samples to the federal schedules, we note that greater than 94% of vehicles operate at a power intensity higher than occurs in the urban and highway schedules.

These results imply that having an electric motor and battery power capable of driving the urban schedule may not satisfy the vast majority of drivers’ needs. To understand this fully, the *peak* power demands and vehicle’s constraints must be evaluated. As will be shown later, even with sufficient energy on-board the engine will need to operate frequently in order to drive an urban-capable vehicle in a blended fashion. On the other hand, if a vehicle has the ability to run the US06 schedule on electric power alone, that vehicle can

satisfy the majority of vehicle usage in the RTS without using the engine.

EPA highway, urban and US06 cycles are also plotted in this figure.

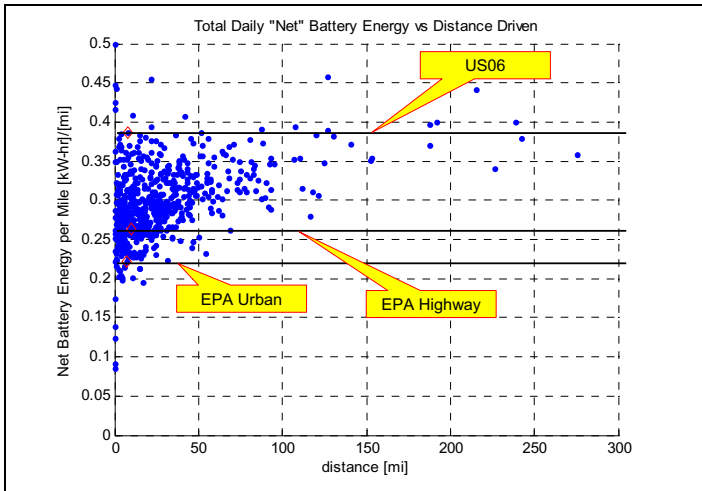


Figure 9a - RTS vehicle power intensity versus daily distance driven

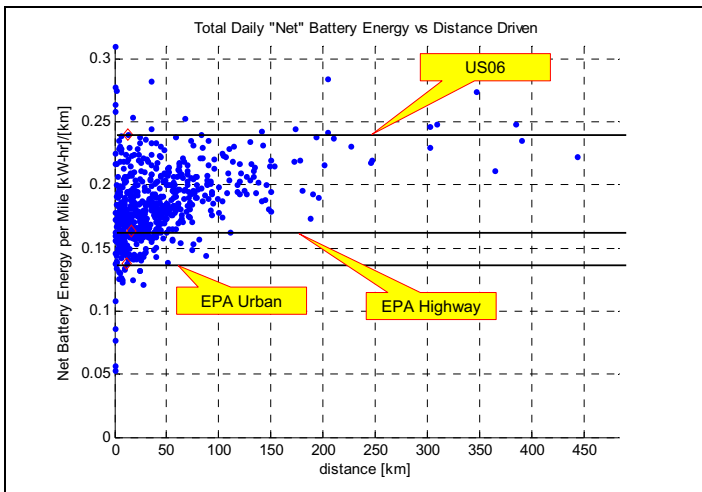


Figure 9b (metric) - RTS vehicle power intensity versus daily distance driven

The RTS data provides some interesting insights into how vehicles are used in southern California. To see how this usage compares to the existing EPA cycles, the cumulative distribution of energy to accelerate and decelerate a typical mid-sized vehicle versus the instantaneous wheel power was evaluated. This is calculated by sampling the data set at a one hertz rate. The speed and instantaneous acceleration along with a simple vehicle model are used to calculate the instantaneous power at the wheel. The energy is approximated by assuming the power level remains constant for the sample. This form of summarizing the data identifies the amount of energy that cannot be generated or absorbed by a power limited electrical traction system. The bounds on the RTS data are plotted in figure 10. The bound for 10%, 50%, and 90% of the sample are identified. The energy distribution for the

For example, in figures 10 and 11, consider a typical mid-sized vehicle with a powertrain that is limited to 40kW at the wheels for motoring and regeneration. For the urban and highway cycles, only a trivial amount of energy can not be delivered or absorbed. However, for the US06 cycle, almost twenty percent of the energy is delivered at power levels that exceed the electric capability of the vehicle. This power must be delivered by the engine. Additionally, almost twenty percent of braking energy occurs at power levels beyond the electrical limits of the system, limiting the energy recovery.

The distribution of wheel energy from the RTS data shows that the bulk of the vehicle usage is somewhere between the urban and US06 in energy distribution versus wheel power. The urban cycles represent the lower limits on vehicle energy distribution and the US06 represents a reasonable upper limit. Consider the previous example with a 40 kW power limit at the wheel. Since the y-axis of the chart is the cumulative distribution of energy, the amount of energy available which higher power level is found in the tail of the distribution. For example, in figure 10, approximately 78% of the wheel energy occurs at power levels less than 40 kW. Therefore, approximately 22% of the wheel energy occurs at power levels in excess of 40 kW. Of the vehicles in the RTS, a vehicle in the upper 10% percentile of the population of samples from the RTS will have more than 15% of its acceleration energy occurring at power level in excess of 40 kW. Conversely, the same 40kW wheel power limits on regeneration (regen) results in a loss of available regen energy for an upper 10% vehicle from the population of samples.

One interesting conclusion to be drawn from this data is that braking energy is distributed to higher power levels than evaluated in existing testing regimes. This type of customer behavior is not reflected in the testing procedures. With the power limits on current production hybrids, this may explain some of the differences between the testing fuel economy and customer's experiences [7].

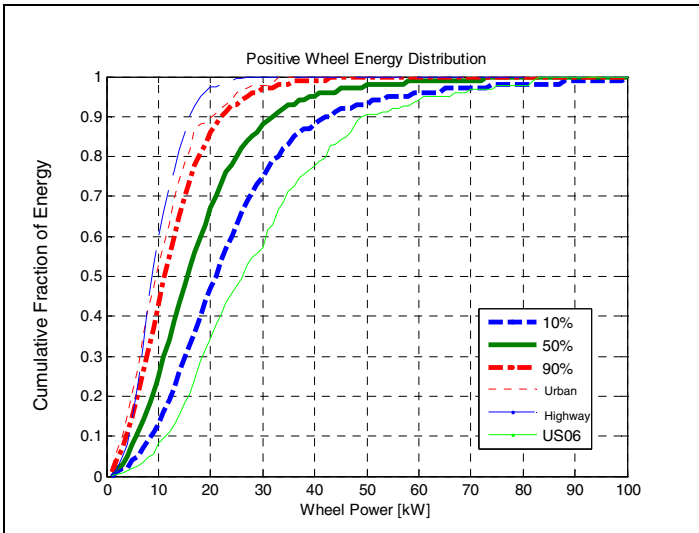


Figure 10 – Distribution of accelerating wheel energy versus wheel power.

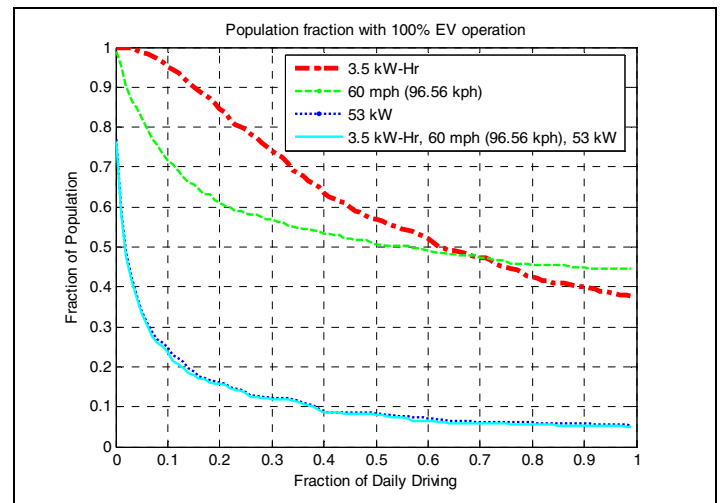


Figure 12 – RTS population's first engine start versus percent of daily distance for various powertrain constraints.

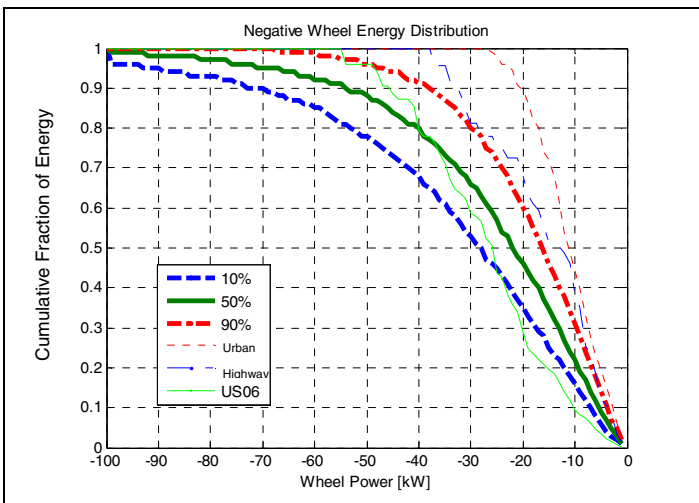


Figure 11 – Distribution of decelerating wheel energy versus wheel power.

Impact of Powertrain Constraints

In addition to considering the distribution of energy in the RTS data, another consideration is when the powertrain constraints will force the first engine start. This is important because it causes the vehicle to transition from EV operation to either blended or charge sustaining operation. While the transition from EV operation does not greatly affect the societal use of fuel, it does affect the regulated pollution emissions and provides a way to understand the energy security a vehicle offers an individual. Because of the scope and detail in the RTS, the impact of speed, power, and energy constraints can be considered. To visualize the impact of these constraints on a population of vehicles, the daily driving distances are normalized to a value between zero and one. Zero represents the start of driving for the day. One represents the end of driving for the day. The percentage of vehicles that can operate as an EV versus the percentage of completed daily driving is plotted in figure 12.

Consider some common constraint combinations for a mid-sized vehicle. Assuming 75% efficiency from battery to wheel for motoring and 60% efficiency from wheel to battery for braking regeneration, the first constraint considered is a battery energy constraint of 3.5 kW-hrs. This energy is sufficient to allow all vehicles to complete the first 5% of their daily driving while operating as an EV. After that point, an increasing percentage of the vehicles transition from EV operation to blended or charge sustaining operation. At the conclusion of driving for the day, less than 40% of the vehicles complete their entire day operating as an EV.

If the powertrain has only a 60 mph (96.56 kph) constraint, such that the engine is forced on when the vehicle speed exceeds 60 mph (96.56 kph), two significant things occur. Firstly, vehicles transition from EV operation earlier in the driving. Secondly, the number of vehicles which can complete daily driving as an EV changes to 43%.

In the absence of other constraints, if the battery and motor is limited to delivering only what is necessary to drive the urban driving schedule, in this case 53 kW, and the engine is used to make up for any differences in required power, the majority of vehicles start their engines before any appreciable driving is complete. Only 6% of the vehicles can complete their day as an EV. This single constraint dominates the transition from EV operation.

If all of the energy, speed, and power constraints are considered together, the resulting vehicle has slightly less EV operation than a vehicle which is constrained by power alone. For these constraints, similar to the limits of an urban-capable PHEV, the power constraint is dominant and limits the vehicle's ability to operate as an EV.

The combination of speed and power constraints has a considerable effect on limiting EV range driving over the

RTS data. It should be noted, that these constraints *would* permit a vehicle to complete the urban cycle as an EV. But the RTS data indicates that real world driving frequently exceeds the power and speed limits of the urban driving schedule. Additionally, the method used to calculate the RTS power levels in this study may underestimate real power variations since a level road grade is assumed. It is expected that were road grade data available, it would indicate higher power levels due to accelerations on grades. Therefore, this evaluation of vehicle operation against RTS data indicates that *only a small fraction of urban-capable PHEVs will actually operate as an EV.*

To compare the relative benefits of electrification, the following powertrains in a typical mid-sized vehicle will be considered:

- **Reference:** a conventional powertrain;
- **HEV:** a powertrain with a 40 kW electrical power constraint;
- **Conversion PHEV:** a PHEV powertrain with a 35 mph (56.32 kph) speed constraint, a 40kW electrical power constraint, and 3.5 kW-hrs of usable electrical energy;
- **Urban-Capable PHEV:** a PHEV powertrain with a 60 mph (96.56 kph) speed constraint, a 53kW electrical power constraint, and 3.5 kW-hrs of useable electrical energy;
- **E-REV:** a powertrain with 8 kW-hrs of useable electrical energy and EV capability not limited by electric power or driving speed.

These vehicles has coast down parameters with F0 equal to 10 N, F1 equal to 0.009 N-s/m, and F2 equal to 0.4392 N-s²/m². The inertia is 1565 kg for the conventional vehicle and adjusted for additional hybrid powertrain and batteries mass.

Fuel Savings

To evaluate the benefits from the different powertrains, the RTS data was used in vehicle simulations to assess fuel savings. The study was performed on a subset of 175 vehicle-days of driving, each with a total distance less than 75 miles (120.7 km). This study required approximately 1500 hours of computer time to execute. The conventional, HEV, conversion PHEV, urban-capable PHEV, and E-REV vehicles were evaluated for each day's data.

Figure 13 shows the average fuel consumption for this population of vehicles. The HEV was able to improve the overall efficiency of operation and reduce the fuel consumption in this population of vehicles by approximately 25%. The PHEVs were able to displace approximately another 30% of HEV's fuel consumption. Significantly, for this test, the conversion PHEV and the urban-capable PHEV provided approximately equal

benefits in fuel savings. Finally, the E-REV, with greater on-board energy storage and the ability to meet all power demands without starting the engine, was able to reduce the PHEV's fuel consumption by more than 50%.

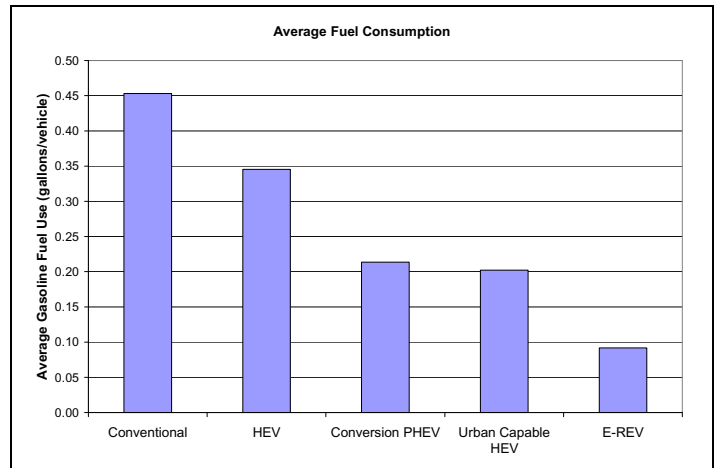


Figure 13a – Average fuel usage over the complete RTS dataset

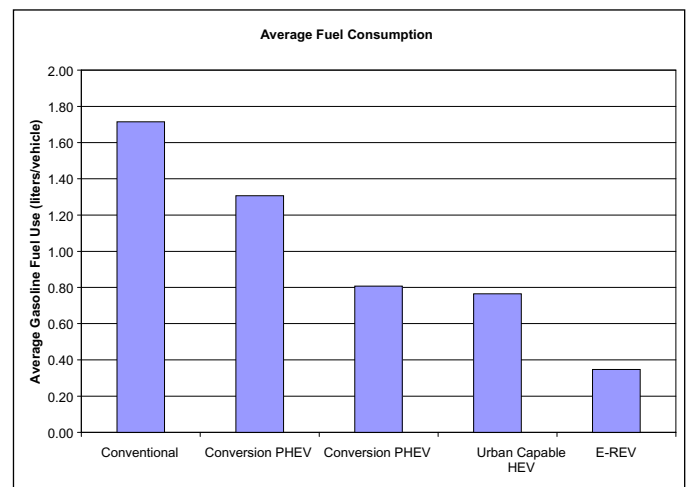


Figure 13b (metric) – Average fuel usage over the complete RTS dataset

Air Pollution Prevention

In addition to fuel usage, the emission of regulated pollutants is a significant concern. Modeling emissions is a complex issue. We propose the following method to simply evaluate the relative benefits of different powertrains.

Several authors have noted that the majority of tailpipe emissions occur within the first minute of engine operation [8,9,10]. After the powertrain thermally stabilizes, the additional emissions are often negligible. To assess the relative merits of different powertrain options, we propose counting whether there is an engine start on a trip. If one or more engine start occurs, then that trip contributes emissions. If no engine start occurs, no emissions are generated. These starts are referred to

as initial trip starts (ITS). The relative benefits of different powertrains are determined by counting the number trips in a reference set and subtracting the number of initial trip starts. The difference between these two values provides a relative measure of pollution prevention.

Because of the previously mentioned issues with powertrain constraints, simply using the EV range to measure the effect of a plug-in vehicle on reducing emissions may be misleading. The EV range considers the energy constraint, but does not consider the impact of power and speed constraints. If those are considered, a data set like the RTS is necessary. Using the RTS, the reduction in initial trip starts (ITS) can be calculated over a population of vehicles.

A simple method to estimate the pollution prevention of a plug-in vehicle is to consider the number of initial trip starts from different vehicle classes. Figure 14 shows the number of initial trip starts for the reference, full hybrid and Plug-in vehicles when examined over the entire RTS dataset. The chart shows that PHEVs reduce the initial starts significantly when compared to a conventional full hybrid. An even more dramatic reduction in initial trip starts occurs when an E-REV is introduced.

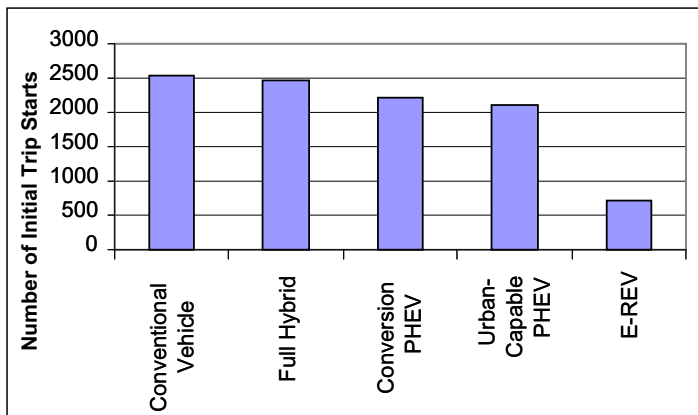


Figure 14 – Initial trip starts over the complete RTS dataset.

The higher energy content, higher power, and higher speed capability reduce and E-REV's initial trip starts by approximately two thirds compared to an urban-capable PHEV.

Another way to consider the effect on emissions of a particular plug-in vehicle is to examine the amount of engine-off driving. To illustrate the effect of differences in powertrain constraints (electric energy, power, and speed capability), a chart that shows the portion of the RTS that can be completed while operating as a pure EV without engine starts is used.

To generate this chart, each day's driving from the RTS data set was simulated to determine when the engine first starts based on the speed, power, and energy

constraints. This distance is used to calculate the percent of daily driving while operating as an EV. The fraction of vehicles which operate as an EV along their daily driving is plotted in figure 15.

A further insight on the effect of the initial trip start on smog formation is the time of day of the initial start. While we note that E-REVs, to much a greater extent than PHEVs eliminate initial starts, it is also true that E-REV initial starts are much more likely to be much later in the driving cycle and contribute to far lower early morning emissions, particularly hydrocarbons (HCs). Further study is warranted into of the effects on peak ozone an the reduced and delayed HC emissions offered by PHEVs, and to a much greater extent E-REVs,

For example, when all PHEVs and E-REVs start their daily driving, 100% of the population is operating as an EV. When the sample of vehicles has driven 10% of the total distance for the day, only 10% of the conversion PHEV's still operate as an EV. In contrast, approximately 24% of the urban-capable PHEV's are still operating as an EV and 98% of the E-REV's are still operating as EVs. By the end of the day, about 3% of the conversion PHEV's completed operating exclusively as EV's, only 5% of the urban-capable PHEVs completed as EV's, and 64% of the E-REV's completed as EV's.

We believe that this is the basis of a significant finding. Even PHEVs modified to provide Urban Capability, 53 kW power and 60mph (96.56 kph) operation, will rarely operate as an EV for the full day's driving. On the other hand, the majority of E-REV drivers will experience a full day of EV driving.

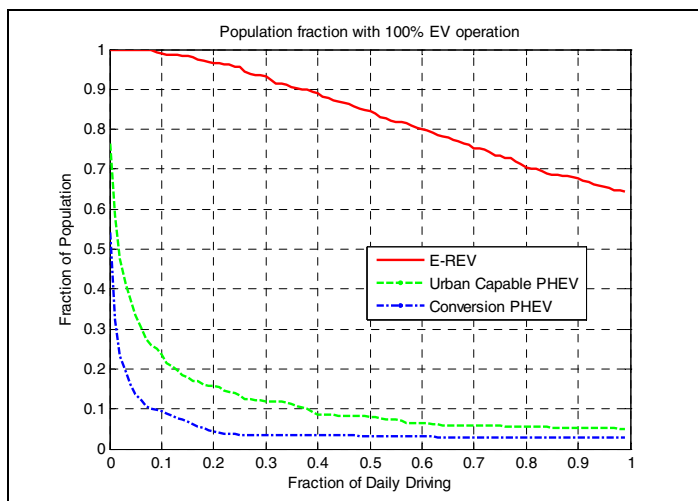


Figure 15 – Percent of population with EV operation through a day's driving.

CONCLUSIONS

As the electrification of the automobile progresses from HEVs, to PHEVs, to E-REVs, the environmental impact of the automobile significantly decreases and energy security increases. Just as the various PHEV's offer significant improvements over HEV's, the E-REV significantly improves over PHEV's.

The PHEV and E-REV are positive steps toward the goals of energy diversification, fuel savings, and emissions reduction. Furthermore and significantly, our findings indicate that:

1. The RTS data set of Southern California drivers contains widespread and significant driving at power levels and speeds beyond that represented by the urban driving schedule
2. An E-REV is more than ten times as likely to finish the day as an EV than an urban-capable PHEV derived from an HEV, when operated in the actual application, as represented by the RTS data set.
3. Similarly, an E-REV will consume, on average, less than half of the petroleum of a PHEV in the real world, if overnight charging is assumed.
4. An E-REV will reduce regulated emissions that are due to initial trip starts by more than 70% when compared to a PHEV in the actual application.
5. "Electric range" when operating on the urban schedule is not a direct measure of a plug-in vehicles' ability to run with the engine off, ability to displace petroleum or ability to reduce regulated emissions in the actual application. Rather, the ability to run with full performance on electric power alone leads to improvements which would be realized in actual application.
6. In the event of a petroleum disruption, an E-REV could support uncompromised vehicle operation for the majority of drivers.

We conclude that electrification that enables E-REVs may be well worth the effort. Specifically designed electric powertrains, incorporating higher power motors and thermal systems, higher energy batteries and integrating them into vehicle structures specifically designed for that purpose will be rewarded with societal benefits realized in real world use. While PHEVs can make improvements when compared to HEVs, An E-REV appears to realize a much greater portion of societal benefits.

Mild and Full HEVs continue to play a growing role in reducing overall consumption and setting commercial

volumes to a level sufficient to develop electrification subsystems. But HEVs do not directly displace petroleum with other energy sources or lead to significant emissions reductions through all electric operation. Conversion PHEVs or even PHEVs with the ability to run the urban schedule are incremental toward these ends, but are of limited because it appears the real world application is in general, much more demanding.

By offering full-performance on electric power alone, the E-REV operates as an EV for the majority of real drivers. By retaining an ICE-powered charging capability, the E-REV overcomes the "range anxiety" limitations of earlier BEVs. We anticipate that the E-REV will be an important and practical step forward in the electrification of the automobile.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

BEV: Battery Electric Vehicle

E-REV: Extend Range Electric Vehicle

ICE: Internal Combustion Engine

ITS: Initial Trip Starts

PHEV: Plug-in Hybrid Electric Vehicle

SCAG: Southern California Association of Governments

EV: Electric Vehicle

NPTS: National Personal Transportation Survey

RTS: SCAG Regional Travel Survey