EVS27
Barcelona, Spain, November 17–20, 2013

Impact of Worldwide Test Procedures on Advanced Technology Fuel Efficiency Benefits

A. Rousseau,[1] Yi Ding[2]
[1]*Argonne National Laboratory, 9700 S. Cass Ave., Lemont, IL, USA, arousseau@anl.gov*
[2]*Ecoles des Mines de Paris, France*

Abstract

In the context of reducing the dependence of transportation on fossil oil, a large number of alternative automobile technologies are considered, including a start-stop system, hybrid and plug-in hybrid vehicles, a full electric vehicle, and fuel cell. While some of these technologies have already been introduced into the market, others are still being developed. To meet future government regulations (i.e., Corporate Average Fuel Economy [CAFE] in the United States, carbon dioxide [CO_2] in Europe…, vehicle energy consumption is critical. Different standard test procedures have been developed to evaluate vehicle performance. The U.S. Environmental Protection Agency (EPA) uses the two-cycle procedure based on the Urban Dynamometer Driving Schedule (UDDS) and the Highway Fuel Economy Test (HWFET); Europe uses the New European Driving Cycle (NEDC), and Japan uses the JC08. As vehicle energy consumption varies from cycle to cycle because of the different driving conditions represented, different powertrain technologies might be more or less effective at reducing fuel consumption. As a consequence, car companies might make different decisions regarding their technology of choice, based on where the technologies are sold. This study assesses the performance of various powertrain technologies in the different standard test cycles in terms of fuel and electrical consumption. The results are then related to car sales in different regions of the world, in an attempt to explain carmakers' choices regarding vehicle technology.

Keywords: Modeling, Regulation, Energy consumption, Electric Drive, HEV

1 Introduction

In the context of reducing the dependence of transportation on fossil oil, a great number of alternative automobile technologies have been proposed, including a start-stop system, hybrid and plug-in hybrid vehicles, full electric vehicles, and fuel cell. Some of these technologies have already been introduced into the market, while others await further development. Sales of hybrid electric vehicles (HEVs) in the United States have been increasing since the introduction of the first model. Similarly, start-stop systems have seen significant market penetration in Europe.

Vehicle energy consumption, in addition to regulations, is a critical customer criterion to purchase a specific vehicle. To inform consumers and set regulations, standard test procedures have been developed to evaluate the performance of different vehicles. The U.S Environmental Protection Agency (EPA) uses the two-cycle procedure based on the Urban Dynamometer Driving Schedule (UDDS) and the Highway Fuel Economy Test (HWFET). Similarly, the New European Driving Cycle (NEDC) is used in Europe, and the JC08 is used in Japan.

The energy saving of powertrain technologies varies significantly from cycle to cycle according to factors such as aggressiveness, speed range, and acceleration. In fact, some of the features of alternative powertrains are designed intentionally to minimize specific fuel-consuming factors. For instance, start-stop systems focus on the fuel consumed during idling. Therefore, these systems offer greater benefits on cycles with a large portion of stop time. Similarly, the benefits of regenerative braking are larger in cycles with frequent decelerations. At the same time, standard drive cycles are designed to represent real-world driving conditions. Therefore, it is instructive to evaluate the performance of various powertrains under these standard test cycles.

This study assesses the performance of various powertrain technologies on current standard test cycles in terms of energy consumption. The results are then related to car sales in different regions of the world in an attempt to explain carmakers' choices regarding vehicle technology.

2 Approach

Using Autonomie [1], different powertrain configurations and component technologies were selected to represent 2015 technologies for three component technologies risk levels: low, medium, and high. Specific vehicles were then sized to meet similar performances and simulated in different worldwide standard test cycles. The energy consumption results simulated were then compared and related to drive cycle parameters such as mean speed, stop time, and stop frequency.

2.1 Powertrain Configurations

Vehicles representing the midsize class were simulated over a variety of powertrain technologies, including:

- Conventional gasoline (conv)
- Conventional diesel
- Power-split HEV spark-ignition (SI) (HEV)
- Power-split Plug-in HEV (PHEV) 10 (PHEV10)
- GM Voltec extended range (PHEV40)
- Series Fuel Cell (FC) HEV (FC HEV or FCV)
- Electric fixed-gear (FG) with 100-mile range on UDDS (battery electric vehicle [BEV] FG 100)
- Electric fixed-gear with 300-mile range on UDDS (BEV FG 300)
- Electric with 2 speed transmission and 100-mile range (BEV automatic mechanical transmission [AMT] 100)
- Electric with 2 speed transmission and 300-mile range (BEV AMT 300)

2.2 Vehicle Sizing

When sized, the vehicles have to meet certain vehicle technical specifications:

- For conventional:
  - Minimum time for an acceleration (0 to 60 mph, 9 seconds),
  - Minimum time for passing (50 to 80 mph, 9 seconds), and
  - Vehicles are sized to perform at a 6% grade at 65 mph at gross vehicle weight.
- For full HEVs, in addition:
  - Minimum engine peak power is 70% of maximum between requirements from acceleration and grade performances,
  - Capture regenerative power on UDDS cycle, and
  - For PHEVs, in addition, the vehicle must be able to run UDDS on electric mode for the PHEV10 and a US06 for the E-Rev.

Automated vehicle sizing algorithms were used to rigorously define the characteristics (i.e., power, energy, weight…) of each component of the vehicle to provide consistent results.

2.3 Driving Cycles

Drive cycles provide a speed-time profile and are used to assimilate driving conditions on a laboratory chassis dynamometer for the evaluation of energy consumption and exhaust emissions.

Driving cycle design is at the center of the standard. There are multiple ways of developing a driving cycle. A “modal” (or polygonal) cycle is composed theoretically with various driving modes of constant acceleration, deceleration, and speed. An example is the European NEDC cycle. Another option involves gathering actual driving data and designing the cycle using the Markov chain. These cycles are called “transient” and are often more dynamic, reflecting more rapid acceleration and deceleration patterns experienced during on-road conditions. [2]

At present, countries and organizations have developed their own test cycles. These include the UDDS and HWFET in the United States [3], NEDC in Europe [4], and Japan1015 and the new JC08 in Japan. Currently, a new cycle, called “Worldwide harmonized Light duty driving Test Cycle” (WLTC) [5], is being developed. It aims at representing typical driving conditions around the world by basing itself on a combination of collected in-use data and suitable weighting factors of China, Europe, South Korea, and the United States. The cycle, once put in place, is expected to replace some or all of the current cycles. This study focuses on the UDDS, HWFET, JC08, NEDC, and WLTC driving cycles. The five cycle test procedure available in the United States is not considered.

Any driving cycle can be characterized by parameters such as mean/max speed/acceleration, stopping frequency, and stopping time percentage. Table 1 lists the main cycle parameters. As indicated in the table, low-speed cycles are generally accompanied by frequent stops, which characterizes urban driving conditions.

Table 1: Standard Drive Cycles Main Parameters

		JC08	UDDS	NEDC	WLTC	HWFET
Max accel.	m/s^2	1.69	1.48	1.07	1.88	1.43
Mean accel.	m/s^2	0.43	0.50	0.59	0.41	0.19
Max decel.	m/s^2	1.22	1.48	1.43	1.52	1.48
Max speed	mph	50.70	56.70	74.60	81.60	59.90
Mean speed	mph	15.21	19.66	20.95	28.85	48.49
Mean running speed	mph	21.55	24.14	27.77	33.06	48.58
Distance	miles	5.09	7.48	6.87	14.43	10.29
Stop frequency	per miles	2.17	2.28	1.90	0.56	0.10
Stop time pct.		29.65%	18.85%	24.83%	13.00%	0.52%
Cruising time pct.		0.58%	6.77%	38.51%	0.49%	16.60%
Accel. time pct.		36.13%	39.71%	20.91%	44.03%	44.18%
Decel. time pct.		33.64%	34.67%	15.75%	42.48%	38.69%

In addition, adjustments can be applied to account for the difference between real driving and laboratory testing. This is the case for conventional vehicles in the United States where two cycles are weighted. In addition, further adjustments can also be applied for alternative powertrains like PHEVs. On the other hand, electricity consumption is not subject to adjustment.

3 Simulation Results

This section discusses the fuel and electrical consumption results for each simulation. For comparison, the cycles are sorted according to their mean speed from low to high. Unless mentioned otherwise, the bar charts were drawn based on the medium risk case, while the high and low risk cases are shown by the error bars. In Section 3.2, a brief analysis explains the fuel savings origins and the impact of cycles on various parameters, including idle consumption, regenerative brake benefits, and component efficiency

3.1 Drive Cycle Results

Figure 1 shows the fuel consumption ratio of micro, mild, and full HEVs compared with their respective conventional vehicle. The highest benefits due to electrification are achieved in the JC08 cycle, followed by the NEDC. The U.S. Combined cycle and WLTC offer similar levels of savings.

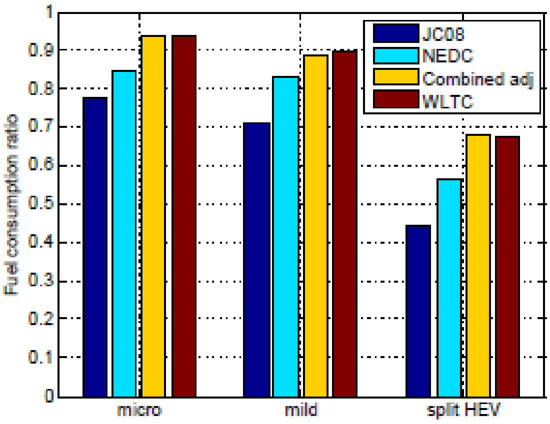

Figure 1: Fuel Consumption Ratio of Micro, Mild, and Full HEVs Compared with Their Respective Conventional Vehicle

Fuel consumption results in Figure 2 (excluding the adjusted U.S. Combined cycle) reveal that conventional vehicles favor high-speed cycles like the HWFET and are penalized in low-speed cycles with low power demands and high idling time. Micro hybrids offer fuel savings ranging from 8%

to 25%. The improvement from micro to mild hybrid is not significant. This is because mild hybrids only offer small regenerative braking energy and limited assist compared with micro hybrids. Full hybrids improve fuel economy considerably, especially for low-speed driving cycles such as the JC08. In any case, this comparison should be combined with cost evaluation.

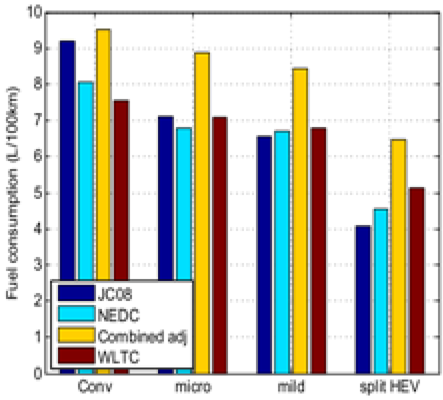

Figure 2: Fuel Consumption of Micro, Mild, and Full HEVs

Table 2 provides the fuel consumption ratio for a sample of powertrain configurations compared with the combined drive cycle. Results show that while the WLTC and the combined drive cycle show similar benefits for the different configurations, both the JC08 and the NEDC are much more favorable to electrification than other cycles.

Table 2: Fuel Consumption Ratio Compared with the Combined Drive Cycle

	JC08	NEDC	Combined	WLTC
Conv	0.97	0.85	1.00	0.80
Micro HEV	0.80	0.77	1.00	0.80
Mild HEV	0.78	0.79	1.00	0.80
Split HEV	0.63	0.70	1.00	0.79

Figure 3 shows the fuel consumption ratio for both FC HEVs and internal combustion engine (ICE) HEVs compared with conventional vehicles. The ratio compared with the conventional vehicles is almost constant. This is because fuel cell vehicles are impacted by the cycles in a similar way as conventional ones due to the vehicle level control strategy which links wheel power demand to fuel cell power.

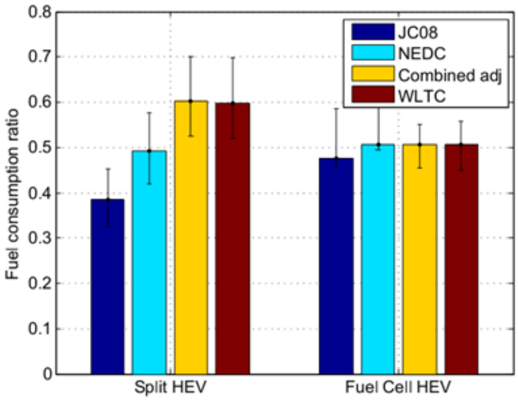

Figure 3: Fuel Consumption Ratio of Full HEVs and Fuel Cell HEVs Compared with Their Respective Conventional Vehicle

Figure 4 represents BEV electrical consumption over the different driving cycles. The electrical consumption is almost constant from cycle to cycle, except for the WLTC. This indicates that under test conditions, BEVs would be less sensitive to driving cycles than other powertrains. This can be explained by the high efficiency of electric machines across different operating conditions. However, one needs to consider that the standard tests are all performed at a temperature of 20°C.

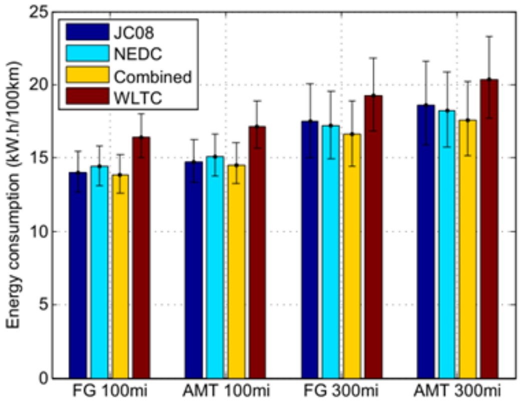

Figure 4: BEV Electrical Consumption

PHEV energy consumption has to be represented by both fuel and electrical consumption. The results are shown in Figures 5 and 6. The WLTC is missing because the procedure does not currently define a utility factor to weight the charge depleting (CD) and charge sustaining (CS) modes; thus it is difficult to compare it with other cycles. In addition, the two consumptions are presented together in Figure 7 by a scatter chart to assess the energy displacement.

Figure 5 shows that for PHEV10, gas consumption increases with the cycle mean speed/aggressiveness. The trends are similar to the HEVs. This is because PHEV10s have similar operating conditions than HEVs, with the exception of longer electric modes (i.e., later engine starts). PHEV40s, however, show almost constant fuel consumption as the engine is operated in similar operating conditions regardless of the vehicle power demand.

Figure 7 shows how energy is displaced from gasoline to electricity when switching from PHEV10 to PHEV40.

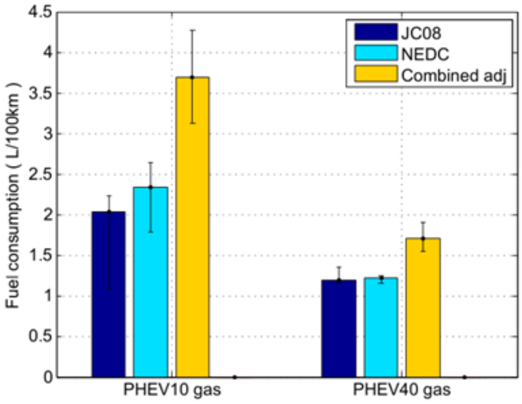

Figure 5: PHEV Fuel Consumption

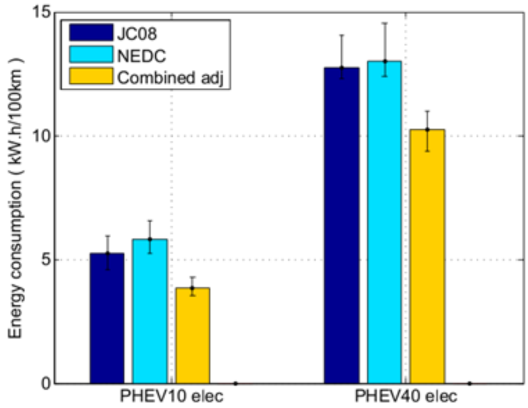

Figure 6: PHEV Energy Consumption

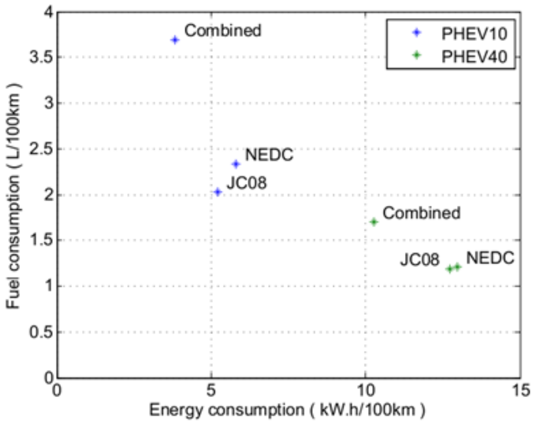

Figure 7: PHEV Fuel and Energy Consumptions

3.2 Fuel Saving Origins

Fuel savings are achieved through different advanced technologies. Each benefit is influenced by cycles in different ways. In this section, we have analysed the impact of cycles on:

- Idle consumption,
- Regenerative brake benefits,
- Efficiency of powertrain components, and
- Engine ON/OFF events.

Idle Consumption

Figure 8 shows the portion of fuel consumed during idling for the different drive cycles considered. Since fuel savings of micro-hybrids are realized almost solely by removing idle fuel consumption, their benefits on the new WLTC will certainly be lower than for the current JC08 cycle in Japan, potentially influencing the penetration of the technology in the market.

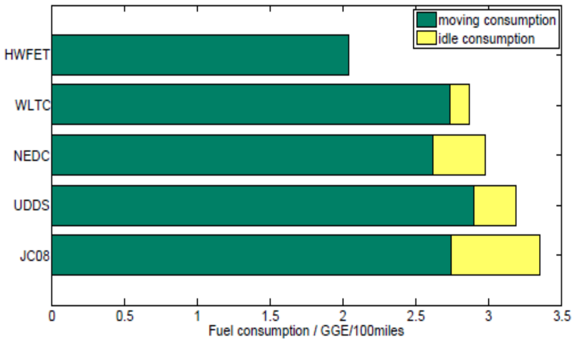

Figure 8: Idle Consumption of Conventional Vehicles

Engine Efficiency

Figures 9 and 10 show the average engine efficiency for each powertrain considered over the different standard drive cycles. One of the issues of conventional vehicles is due to the low average engine efficiency in urban driving conditions. One of the benefits of power-split hybrids is to increase the average engine efficiency by decoupling its speed from the vehicle speed. With a higher average cycle speed, such as for the WLTC, the benefits of hybridization for the low-speed cycles, such as the JC08 or the UDDS, would significantly decrease. As a result, the technology would not appear as attractive to car companies to meet their CO_2 requirements.

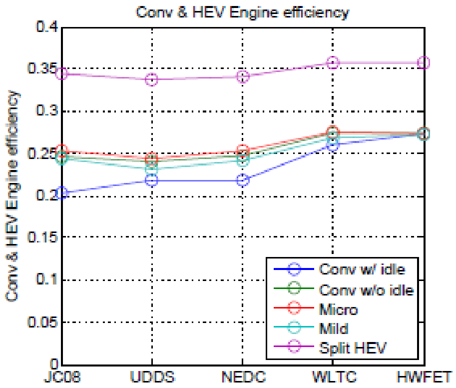

Figure 9: Average Engine Efficiency for Conventional, Micro, Mild, and Full HEVs over Different Cycles

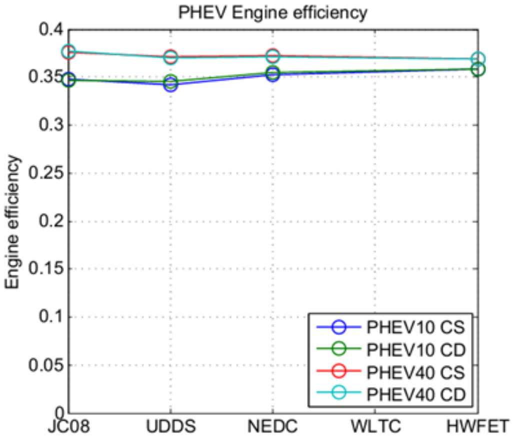

Figure 10: Average Engine Efficiency for PHEVs over Different Cycles

Engine ON/OFF Events

The frequency of engine ON/OFF events and engine ON percentage are indicators of the engine assist in a hybrid vehicle. According to Figures 11 and 12, the values vary depending both on cycles and powertrains (operation mode). In general, higher speed cycles like WLTC and HWFET are characterized by a lower number of engine ON/OFF events, but they have a longer engine ON time in between events.

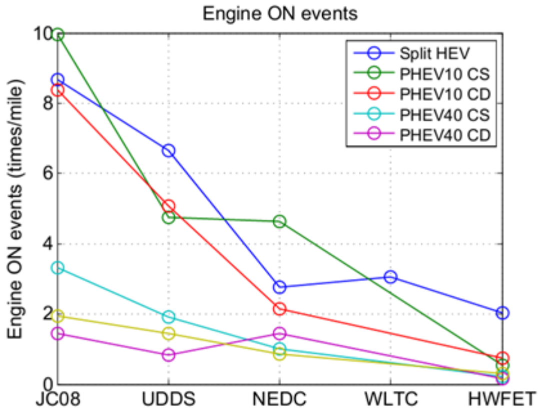

Figure 11: Engine ON/OFF Events

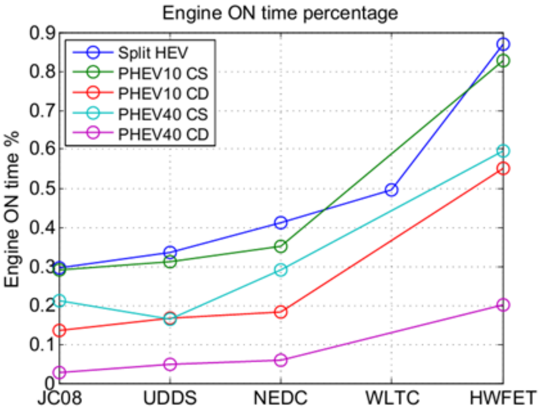

Figure 12: Engine ON Time Percentage

3.3 Economic Analysis

The levelized cost of driving (LCD) was used to evaluate the benefits of different technologies. The 2015 U.S. Department of Energy (DOE) cost targets for each component technology were used to assess the manufacturing costs.

While the vehicle costs were maintained constant across all drive cycles, the fuel prices were varied per region using the factors shown in Figure 13 and the United States as a reference.

	Gasoline	Electricity
France	×2.2	×1.7
Germany	×2.2	×3.2
Japan	×2.0	×2.0

Figure 13: Adjustment for International Fuel Price

Figure 14 shows the results when assuming an adjusted fuel price for a 3-year payback. The HEV, PHEV10, and BEV100 are able to recover the additional cost for a 3-year analysis period assumption. PHEV40 is also able to rival the cost of conventional vehicles when considering the high case scenario. A BEV with a 300-mile range, however, will not provide an acceptable return on investment.

Figure 15 shows the results when assuming an adjusted fuel price for a 15-year payback. More models can offer profits at the end of the life time. HEV, PHEV10, and BEV100 save around 20% compared with a conventional vehicle. PHEV40 and FC HEV almost equal the conventional ones.

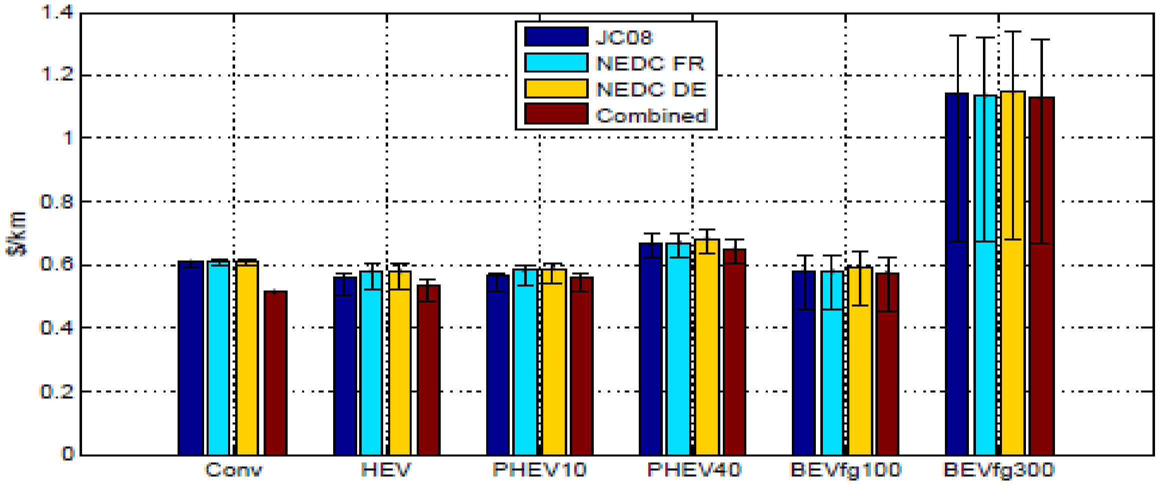

Figure 14: Levelized Cost – 3-year Payback

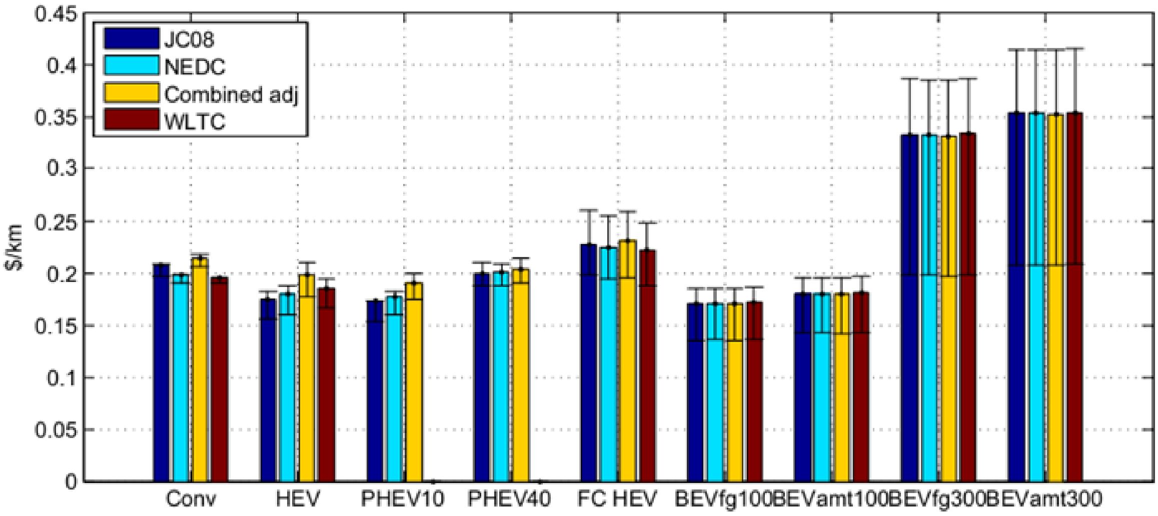

Figure 15: Levelized Cost – 15-year Payback

3.4 Impact of Standard Cycles on Market Shares

The market of alternative vehicle technologies is disparate throughout the world. For example, among the commercialized models, full hybrid is much more popular in the United States than in Europe. Statistics show that in 2010, HEV constituted 3.9% of total sales, while in the European Union the share was 0.6%. In contrast, start-stop systems have penetrated the European market, but there are few in the United States. In Japan, sales of full HEVs have significantly increased in the past 2 years. While numerous factors influence customers' choices, our analysis showed that the choice of the standard drive cycle is of critical importance. Indeed, HEVs benefit the JC08 much higher than other cycles, partially explaining the volume of sales in Japan. Micro and mild HEVs show very good gains on the NEDC.

The benefits of full HEVs are not as large, partially explaining the technology choices in Europe.

Following the analysis, one might expect a change of technology in the near future with the introduction of the WLTC as a replacement of some (if not all) the standard cycles. For example, since the WTLC is not as favourable as the JC08, one might expect full HEV sales to be affected in Japan.

4 Conclusions

The study objectives were to evaluate the fuel and electrical consumption performance for several alternative powertrain technologies on standard test procedures, including JC08, NEDC, Combined, and WLTC. Powertrain configurations considered included conventional micro and mild HEV, full HEV, as well as PHEVs, FC HEVs, and BEVs. The vehicles have been defined to represent the potential of near-term technologies.

The simulation results showed that standard driving cycles significantly impact fuel and electrical consumption. Conventional and series FC HEVs favor high speed with little idling, while power-split HEVs offer higher fuel benefits on low-speed cycles. PHEV40s and BEVs are not significantly impacted by drive cycles.

To understand the differences between cycles, a selected number of parameters were analyzed, including idle consumption, component efficiency, and ICE ON/OFF events. Through an economic analysis, the study showed that several powertrain configurations, with the exception of the BEV300, would be cost-effective based on the 2015 DOE cost target.

Finally, when looking at the current market share of the technologies worldwide, it appears that there is a correlation with the current drive cycles. With a new drive cycle (WLTC) soon to be adopted in some countries, future studies will need to look at its impact on future technology market penetrations.

Acknowledgments

This work was supported by DOE’s Office of Vehicle Technologies. The support of David Anderson is gratefully acknowledged. The submitted manuscript has been created by the UChicago Argonne, LLC, Operator of Argonne National Laboratory (“Argonne”). Argonne, a U.S. Department of Energy Office of Science laboratory, is operated under Contract No. DE-AC02-06CH11357. The U.S. Government retains for itself, and others acting on its behalf, a paid-up nonexclusive, irrevocable worldwide license in said article to reproduce, prepare derivative works, distribute copies to the public, and perform publicly and display publicly, by or on behalf of the Government.

References

[1] Argonne National Laboratory, “Autonomie.” http://www.autonomie.net/. Accessed Jan. 2012.

[2] F. Zannikos, S. Stournas, E. Tzirakis, and K Pitsas, “Vehicle Emissions and Driving Cycles: Comparison of the Athens Driving Cycle (adc) with ece-15 and European Driving Cycle (edc)” *Global NEST Journal*, 8(3):282–290, 2006.

[3] U.S. Standard Vehicle Test Procedures, 2012. http://www.epa.gov/fueleconomy/regulations.htm.

[4] European Test Procedures. E/ECE/324 and E/ECE/TRANS/505.

[5] Worldwide Test Procedures https://www2.unece.org/wiki/pages/viewpage.action?pageId=2523179.

Authors

Aymeric Rousseau is the Manager of the Vehicle Modeling and Simulation Section at Argonne National Laboratory. He received his engineering diploma at the Industrial System Engineering School in La Rochelle, France, in 1997. After working for PSA Peugeot Citroen in the Hybrid Electric Vehicle research department, he joined Argonne National Laboratory in 1999, where he is now responsible for the development of Autonomie and its applications.