Published 08/11/2017
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doi:10.4271/2017-01-9379

Fuel Consumption Sensitivity of Conventional and Hybrid Electric Light-Duty Gasoline Vehicles to Driving Style

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ABSTRACT

Aggressive driving is an important topic for many reasons, one of which is higher energy used per unit distance traveled, potentially accompanied by an elevated production of greenhouse gases and other pollutants. Examining a large data set of self-reported fuel economy (FE) values revealed that the dispersion of FE values is quite large and is larger for hybrid electric vehicles (HEVs) than for conventional gasoline vehicles. This occurred despite the fact that the city and highway FE ratings for HEVs are generally much closer in value than for conventional gasoline vehicles. A study was undertaken to better understand this and better quantify the effects of aggressive driving, including reviewing past aggressive driving studies, developing and exercising a new vehicle energy model, and conducting a related experimental investigation. The vehicle energy model focused on the limitations of regenerative braking in combination with varying levels of driving-style aggressiveness to show that this could account for greater FE variation in an HEV compared to a similar conventional vehicle. A closely matched pair of gasoline-fueled sedans, one an HEV and the other having a conventional powertrain, was chosen for both modeling and chassis dynamometer experimental comparisons. Results indicate that the regenerative braking limitations could be a main contributor to the greater HEV FE variation under the range of drive cycles considered. The complete body of results gives insight into the range of fuel use penalties that results from aggressive driving and why the variation can be larger on a percent basis for an HEV compared to a similar conventional vehicle, while the absolute fuel use penalty for aggressive driving is generally larger for conventional vehicles than HEVs.

CITATION: Thomas, J., Huff, S., West, B., and Chambon, P., "Fuel Consumption Sensitivity of Conventional and Hybrid Electric Light-Duty Gasoline Vehicles to Driving Style," *SAE Int. J. Fuels Lubr.* 10(3):2017, doi:10.4271/2017-01-9379.

INTRODUCTION

The US Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy and the US Environmental Protection Agency (EPA) jointly maintain a fuel economy (FE) website (www.fueleconomy.gov), in part to fulfill their responsibility (under the Energy Policy Act of 1992) for providing accurate FE information to consumers. The site provides EPA FE ratings for light-duty cars and trucks from 1984 to the present and information related to energy use such as efficiency-related vehicle technologies, alternative fuels, driving tips, and vehicle maintenance tips. The Oak Ridge National Laboratory (ORNL) conducts studies to validate and improve these tips [1, 2, 3, 4, 5, 6, 7, 8] as part of its contractual obligations to DOE. The main reason for providing information to the public is to increase understanding of vehicle FE issues and to assist consumers in making informed decisions related to their vehicle usage (including driving style), with the goal of lowering energy consumption. One specific goal of this study is to quantify the fuel penalties associated with aggressive driving and subsequently inform the public via the website.

A topic of great interest is fuel use variation with driving style, particularly aggressive driving, which has important implications pertaining to energy consumption, and potential production of greenhouse gases (GHG) and other pollutants. Discouraging high fuel use has global implications and is of interest to a broad audience. Understanding how driving style alters fuel consumption (FC) can have applications which include estimating benefits realized through improved traffic flow in general, and the use of "smart" traffic control systems and autonomous vehicles.

The concept of "aggressive driving" is subjective, and therefore, quantifying the effect of aggressive driving on FC or FE in a meaningful way is problematic. Similarly, "calm" or "normal" driving also is not well-defined. Both calm and aggressive driving can occur over a broad range of circumstances and with a very wide variety of vehicles, giving an enormous "phase space" that could be explored. To address this complex topic, several previous studies were examined, a new vehicle energy model was developed and applied, and a related experimental effort was conducted.

Five previous studies [9, 10, 11, 12, 13] that directly address aggressive driving were reviewed for their relevant content and compared to recent ORNL experimental results to give some general insight on the FC penalty for aggressive driving. Note that each study had different goals and methods, which is not surprising considering the difficulty and broadness of the topic. Only one study included multiple conventional vehicles (gasoline and diesel fueled engine powered vehicles which do not have an electric powertrain and which currently dominate the US market), and one study included several alternative powertrains. All reviewed studies included hybrid technology and at least one conventional powertrain vehicle for comparison. A study quantifying the fuel penalty associated with increasing steady highway speeds [5,14] was also included because driving faster than the posted speed or faster than most of the traffic on motorways or interstate highways can be considered a form of aggressive diving.

Each of the reviewed studies is summarized. These summaries are followed by sections on recent ORNL modeling and experimental efforts. A short section then examines and compares the characteristics of the drive cycles featured in the various studies (with further details in Appendix A) and ways the studies are complementary. This is followed by observations and conclusions targeting the effects of aggressive driving on FE or FC. The results in this paper are generally given in terms of the preferred engineering metric of FC (fuel use per unit distance) rather than FE (such as miles per gallon). Aggressive driving also has safety implications, but safety is not addressed in this paper.

OBSERVATION OF HYBRID AND CONVENTIONAL VEHICLE FUEL ECONOMY VARIABILITY

Consumers are encouraged to voluntarily submit on-road FE to "My MPG" (

https://www.fueleconomy.gov/mpg/MPG.do?action=garage), where these data are collected for both consumer feedback and analysis. These data were examined in a 2011 study by Lin and Greene [15] to compare the self-reported data to the EPA and US Department of Transportation vehicle label FE. Figure 1 summarizes the data graphically. Detailed analysis of the data and the data quality are given in the 2011 study [15] and is not discussed here.

It was observed from the data collected that the dispersion of miles per gallon values for hybrid electric vehicles (HEVs) was larger than that seen for conventional gasoline vehicles. Simple visual observation of the data and statistical analysis verify this. In contrast, most HEVs show much less difference in adjusted (label) FE when the results of the (regulatory) standard EPA city test cycle are compared to the highway test cycle, and multiple examples are given in Table 1. From this observation, one might hypothesize that significantly less mile-per-gallon variation should be experienced with HEVs compared to conventional vehicles. However, consumers drive their own unique and variable drive cycles rather that the regulatory cycles. In general, the dispersion in FE values is thought to be caused mostly by driving cycle differences (which are influenced by individual driving styles), with other factors such as ambient conditions, use of auxiliary loads, and added vehicle mass also contributing to this dispersion of FE values.

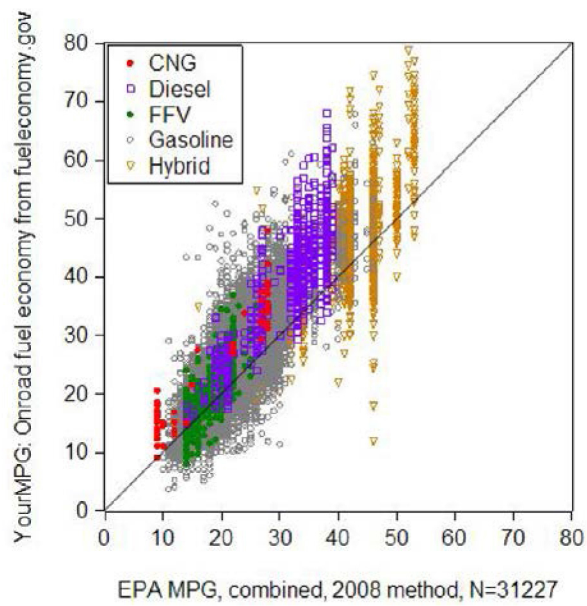

Figure 1. Self-reported miles per gallon (mpg) values from www.fueleconomy.gov plotted against the EPA label values. CNG = compressed natural gas; FFV = Flexible Fuel Vehicle

Table 1. Label FE values for selected conventional and hybrid sibling vehicles.

Vehicle models	Conventional gasoline City/Highway (mpg)	Hybrid gasoline powertrain City/Highway (mpg)
2015–2016 Ford Fusion	24/36	44/41
2012 Hyundai Sonata/Kia Optima	24/34	34/39
2017 Honda Accord	27/36	49/47
2008–2009 Toyota Camry	21/31	33/34
2014–2016 Toyota Camry	25/34	40/37
2016 Chevrolet Malibu	27/37	47/46
2012–2013 Honda Civic	30/39	44/44
2014–2015 Nissan Pathfinder	20/27	25/28
2008–2010 Highlander, all-wheel drive (AWD)	17/23	27/25
2016 Murano AWD	21/28	26/29

Assuming real-world driving often involves more aggressive acceleration and braking than is captured by the regulatory city and highway cycles, it was hypothesized that HEV FE or FC may be more sensitive to such relatively aggressive driving than conventional vehicles. In the sections that follow previous studies are reviewed, and the results appear to support this hypothesis. It was further hypothesized that in some cases a large contributor to this higher sensitivity stems from the characteristics of regenerative braking (RB) systems [16]. An ORNL study exploring this contention is presented in later sections.

REVIEW OF AGGRESSIVE DRIVING STUDIES

European On-Road Study

A relatively ambitious on-road study was performed by Lenaers [9] in Belgium using four similar-size sedans, four levels of driving behavior, and three types of driving routes (a 4 × 4 × 3 test matrix). Of the four driving behaviors, three were identified as "new," "relaxed" and "normal." In some cases all three gave relatively similar FC results, with the normal level most often having the highest FC of the three. The fourth behavior was identified as "aggressive" and resulted in significantly higher FC. To simplify the results, only the relaxed, normal, and aggressive driving styles are compared here. The new driving style featured purposeful shifting patterns to keep engine speed low and in-gear decelerations to cause fuel cut-off, but this strategy only occasionally improved on the relaxed driving style.

Vehicles

The vehicles were sedans of similar size, listed below. The study did not provide model year information but rather the first year each vehicle was operated (year given in the list) and noted all had low odometer readings. Apart from the Prius, the vehicles were apparently equipped with manual transmissions, as implied in the text of the study (which discusses shifting techniques used for one of the driving styles).

1. Peugeot 307: 1.6 L, 80 kW gasoline engine (2006)
2. Peugeot 307: 1.6 L, 80 kW diesel engine (2006)
3. Seat Leon: 1.6 L, 75 kW engine retrofitted (from gasoline) for liquefied petroleum gas (LPG) and fueled with a mixture of 50% propane and 50% butane (2006)
4. Toyota Prius II: 1.5 L, 57 kW engine; 50 kW electric motor; gasoline hybrid (2005)

Driving Routes

Three driving routes were examined, named "urban," "rural," and "motorway," with average speeds of 20-26 km/h, 44-50 km/h, and 100-106 km/h, respectively. The driving styles identified as relaxed, normal, and aggressive were characterized as having average acceleration values of 0.45 to 0.65 m/s^2, 0.65 to 0.80 m/s^2, and 0.85 to 1.10 m/s^2, respectively, for the urban and rural routes (not the motorway route). Each vehicle was driven 3 or 4 times for each route and driving style combination. This was described as a small number of repeats, but effort was put into selecting routes and using driving techniques such that driving consistency was achieved. In cases of anomaly due to traffic problems or other reasons, that specific driving test was discarded.

Fuel Consumption Results

The measured FC increases due to aggressive driving are summarized in Tables 2 and 3. Urban driving showed very high sensitivity to driving style, with a 47%-68% FC increase (ignoring the odd result from the LPG vehicle) comparing aggressive to normal driving styles. The rural route also showed high FC increases for aggressive versus normal driving for the gasoline and diesel vehicles (41% and 46%, respectively) and 18%-19% for the HEV and LPG vehicles. The motorway route tests resulted in modest increases in FC, with 5%-12% increase reported for aggressive versus normal driving styles. The study notes that because traffic rules were obeyed, including speed limits, the level of aggressiveness for the motorway driving was limited.

Table 2. FC comparison for normal and aggressive driving for three driving routes in [9].

	FC (L/100 km)			
Driving style-route	Gasoline vehicle	Diesel vehicle	Gasoline HEV	LPG vehicle
Relaxed urban	10.52	5.75	4.98	12.23
Normal urban	10.80	7.93	6.39	13.72
Aggressive urban	18.13	11.63	10.15	14.96
Relaxed rural	6.18	4.48	4.47	8.15
Normal rural	6.37	4.47	4.37	8.82
Aggressive rural	8.97	6.51	5.15	10.53
Relaxed motorway	7.11	5.09	5.72	9.79
Normal motorway	7.49	5.46	5.82	9.56
Aggressive motorway	7.92	5.74	6.50	10.11

Table 3. Relative change in FC for normal versus aggressive driving for three driving routes in [9].

	FC increase: Aggressive compared to normal driving (%)			
Driving route	Gasoline vehicle	Diesel vehicle	Gasoline HEV	LPG vehicle
Urban	67.9	46.7	58.8	9.0
Rural	40.8	45.6	17.8	19.4
Motorway	5.7	5.1	11.7	5.8
	FC increase: Aggressive compared to relaxed driving (%)			
Urban	72.3	102.3	103.8	22.3
Rural	45.1	45.3	15.2	29.2
Motorway	11.4	12.8	13.6	3.3

2005. Argonne Six Vehicle Dynamometer Study

An Argonne National Laboratory (Argonne) vehicle research laboratory study using two HEVs and four conventional vehicles was performed using the EPA Urban Dynamometer Driving Schedule (UDDS, also known as the city test) and the Highway Fuel Economy Test (HWFET) cycles and three variants of each cycle using a speed multiplier technique [10]. The primary objective was to quantify FC changes over these cycles, which vary in intensity (speed, acceleration, deceleration), and to show that HEVs respond differently from conventional gasoline vehicles.

Vehicles

The vehicles listed below were used for the experimental study in [10]. The model years of the vehicles were not specified directly, but the model years could be deduced by the EPA dynamometer target coefficients or other means [11,18] for all except the Honda Insight.

Note that vehicle powertrains often remain essentially the same over several model years, so identifying any year within that range is sufficient for FC applications.

1. 2004 Toyota Prius hybrid I4: 1.5 L, 57 kW (76 hp); continuously variable transmission
2. 2000 Honda Insight, I3: 1.0 L, 50 kW (67 hp); 5-speed manual transmission
3. 2004 Ford Focus, I4: 2.0 L; 4-speed automatic transmission
4. 2004 Toyota Echo, I4: 1.5 L, 80 kW (108 hp); 4-speed automatic transmission
5. 2005 Ford Escape V6: 3.0 L, 145 kW; 4-speed automatic transmission; 4-wheel drive
6. 2003 Jaguar XJ8, V8: 4.2 L, 219 kW; 6-speed automatic transmission

Drive Cycles

UDDS and HWFET cycles where chosen as basic drive cycles in [10]. Four variants of each cycle were defined by simply multiplying the speed by the factors 0.8, 1.0 (the unaltered cycles) 1.2, and 1.4. Figures 2 and 3 offer examples to illustrate the multiplier operation used to define new cycles.

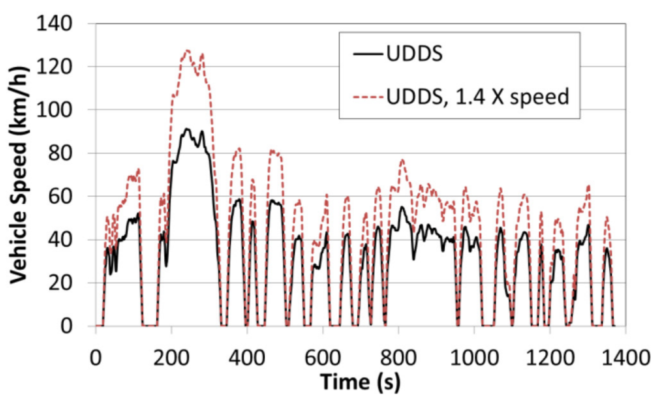

Figure 2. Illustration of applying a 1.4 speed multiplier to the UDDS drive cycle such as in reference [10].

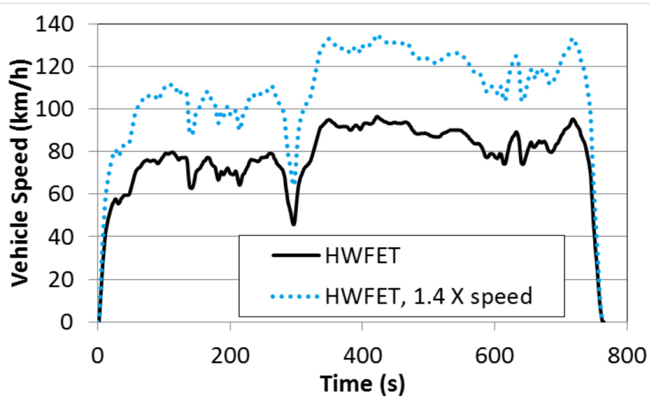

Figure 3. Illustration of applying a 1.4 speed-multiplier to the HWFET drive cycle such as in reference [10].

Fuel Consumption Results

FC values were determined by chassis dynamometer laboratory experiments in [10]. The UDDS experimental FC results for speed-modified cycles with multipliers of 0.8, 1.0, 1.2, and 1.4 are shown in Figures 4 and 5. The percent change in FC relative to the (unaltered) UDDS and HWFET is given in Tables 4 and 5. The reasoning is these cycles feature relatively moderate to low levels of acceleration and deceleration (see Appendix A) and for the purposes of this study are judged to be most representative of normal or "calm" driving. This is a somewhat arbitrary choice, and the 0.8 multiplier cycles are included for comparison. Values for FC were read from plots using plot digitizing software, and there may be small discrepancies compared to the original data.

The results show that FC generally increases with cycle intensity and indicate HEVs are more sensitive in terms of percent FC change over the range of cycles examined compared to the conventional vehicles. The HWFET-based cycle results show larger FC changes, which are driven mainly by aerodynamic drag. More discussion and explanation of the cycles examined and trends in these data will be presented later.

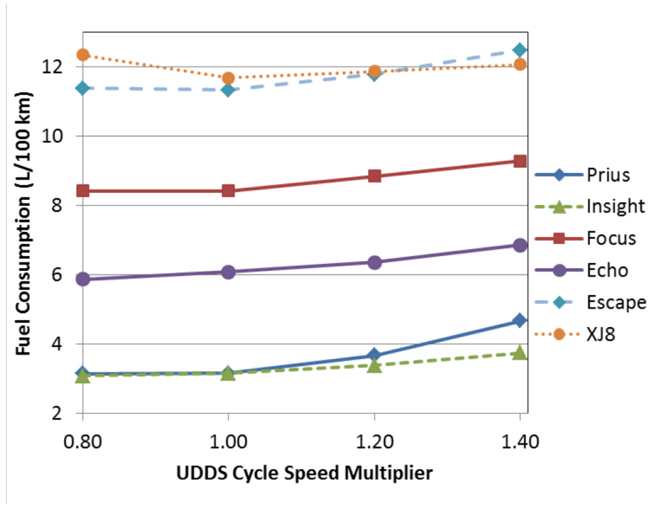

Figure 4. Results for FC for six vehicles tested over the UDDS cycle and intensity variant cycles altered by speed multipliers [10].

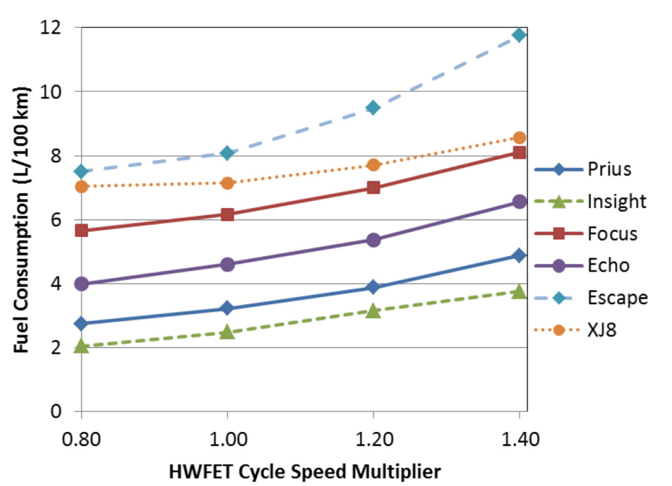

Figure 5. Results for FC for six vehicles tested over the HWFET cycle and intensity variant cycles altered by speed multipliers [10].

Table 4. FC change for six vehicles tested over the UDDS cycle and intensity variant cycles altered by speed multipliers in reference [10].

UDDS cycle	Change in FC relative to the unaltered UDDS cycle (%)					
Speed multiplier	Prius	Insight	Focus	Echo	Escape	XJ8
0.8	−0.5	−2.5	0.0	−3.4	0.4	5.7
1.0	0.0	0.0	0.0	0.0	0.0	0.0
1.2	16.0	7.0	5.1	4.7	3.9	1.6
1.4	47.6	18.5	10.2	12.8	10.1	3.3
	FC (L/100 km)					
0.8	3.15	3.09	8.43	5.88	11.39	12.36
1.0	3.17	3.17	8.43	6.08	11.35	11.70
1.2	3.67	3.39	8.86	6.37	11.79	11.89
1.4	4.67	3.75	9.29	6.86	12.49	12.08

Table 5. FC change for six vehicles tested over the HWFET cycle and intensity variant cycles altered by speed multipliers in reference [10].

HWFET cycle	Change in FC relative to the unaltered HWFET cycle (%)					
Speed multiplier	Prius	Insight	Focus	Echo	Escape	XJ8
0.8	-15.0	-17.6	-8.1	-13.3	-7.0	-1.5
1.0	0.0	0.0	0.0	0.0	0.0	0.0
1.2	20.4	27.2	13.5	16.7	17.6	7.9
1.4	51.2	51.2	31.6	42.7	45.7	20.0
	FC (L/100 km)					
0.8	2.74	2.04	5.66	3.99	7.51	7.03
1.0	3.22	2.48	6.16	4.60	8.07	7.14
1.2	3.88	3.15	6.99	5.36	9.49	7.70
1.4	4.87	3.75	8.11	6.56	11.76	8.57

2007. Argonne HEV and Conventional Vehicle Study

A subsequent 2007 Argonne study [11] featured experimental results from the study just described [10] for the Prius and the Focus and modeling results for these vehicles using the same cycles and variants. The emphasis of the paper was validation and application of a model. A cycle was added for modeling using a 1.6 speed multiplier, which represents driving at excessive speeds, particularly for the HWFET cycle (128 km/h for the UDDS, 154 km/h for the HWFET), but inclusion may have been useful for model validation. The modeling results were similar to the experimental results already reported in the 2005 study [10].

2009. Argonne Plug-In HEV and Conventional Vehicle Experimental Study

A 2009 Argonne study [12] focused on two specialty research plug-in HEVs (PHEVs), noting that PHEVs were not yet available as original equipment vehicles. A Ford Focus was included in the study to allow comparison with a similar size conventional powertrain vehicle.

Vehicles

The vehicles used in reference [12] are listed below. Note that, for the current purpose of this review, the PHEV data are summarized. However, because the PHEVs were prototype vehicles, they have unknown relevance to today's market.

1. Power-split blended Hymotion Prius PHEV
2. Pre-transmission parallel plug-in hybrid electric, all-electric-capable, test vehicle developed by Argonne; referred to as the Modular Automotive Technology Testbed (MATT)
3. 2004 Ford Focus ZX3: 2.0 L gasoline engine, 4-speed automatic transmission [12,17]

Drive Cycles

The drive cycles used for comparison were the UDDS and modifications to this cycle to form a number of variants, but in a different manner than in [10]. The UDDS was modified by intensity scaling factors of 1.1, 1.2, 1.3, and 1.4. However, in this case the drive trace vehicle speed was multiplied by the scaling factor and the drive trace time was divided by the same factor. In this way, the resulting cycles have equal driving distance, a speed trace that increases according to the multiplier, and acceleration/deceleration rates that increase in magnitude by the multiplier value squared. For example, using the 1.4 multiplier, vehicle speed is increased by 40%, cycle duration is shortened to 71% (1/1.4), and acceleration increases by a factor of 1.96 (1.4^2). The baseline UDDS cycle and the cycle intensified by the 1.4 scaling factor are shown in Figure 6.

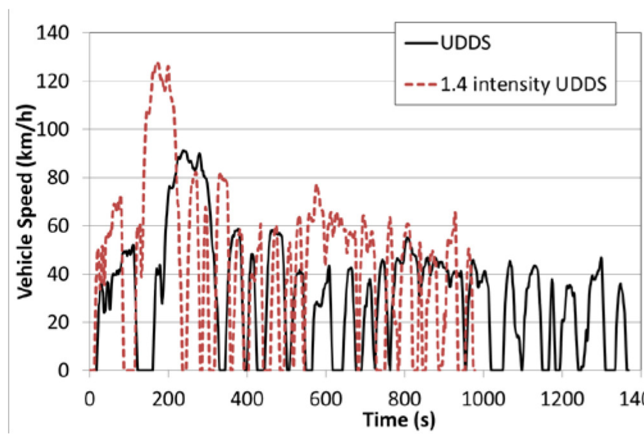

Figure 6. The UDDS drive cycle compared to the same cycle intensified by a 1.4 scaling factor as in [12].

Fuel Consumption Results

A summary of the most relevant FC results from this study is given in Table 6 [12]. The PHEV vehicle data are for battery charge sustaining mode, and therefore they are operating essentially as HEVs. The Ford Focus data were only collected for the 1.2 and 1.4 intensity multiplier cases, while the other vehicles were operated at cycles derived from all four multipliers. The Ford Focus shows a 34% FC increase for the most aggressive case compared to the UDDS cycle, and the PHEVs show 32% and 89% FC increases. Note again that the FC data were digitized from plots in the publications, which may have introduced small errors.

Table 6. FC and FC change with cycle intensity [12].

Drive cycle intensity factor	Ford Focus	Hymotion PHEV Toyota Prius	Argonne MATT PHEV
	FC increase compared to UDDS cycle (%)		
1.0	Baseline	Baseline	Baseline
1.1		7.1	13.3
1.2	10.6	9.8	42.4
1.3		19.9	52.7
1.4	33.7	32.4	89.0
	FC (L/100 km)		
1.0	8.75	6.53	3.47
1.1		6.99	3.94
1.2	9.67	7.17	4.95
1.3		7.83	5.30
1.4	11.70	8.64	6.56

Clemson-ICAR Aggressive Driving Study

A study by the Clemson University International Center for Automotive Research (Clemson-ICAR) examined the effect of driver aggressiveness with the major focus on evaluating the merits of a 48 V mild hybrid system using vehicle modeling methods [13].

Vehicles

The major attributes of the modeled vehicles in [13] are listed below. The study examined a conventional car and virtually the same car with a 48 V mild hybrid system.

1. Conventional compact car
   Weight: 1,300 kg
   Engine: In-line 4-cylinder, 1.9 L, naturally aspirated
   Transmission: 6-speed manual
2. Compact car with mild hybrid system

   Weight: 1,350 kg
   Engine: In-line 4-cylinder, 1.9 L, naturally aspirated
   Transmission: 6-speed manual
   Mild hybrid system: Integrated starter generator and a 48 V, 4.2 Ah lithium ion battery

Drive Cycles

The Clemson-ICAR study used an actual drive cycle database of more than 1,800 trips to establish criteria for levels of aggressive driving based on the first derivative of acceleration (known as “jerk”) and other factors. The trips were divided into thirds based on the chosen criteria and deemed to be calm, normal, and aggressive driving styles. The trips were then also categorized by length as short (less than 6 km), medium (6 to 12 km), and long (greater than 12 km).

Fuel Consumption Results

FC estimates in [13] were generated from a modeling effort for the conventional vehicle (Table 7). Aggressive driving compared to calm driving is estimated to add an average of 25% FC for short trips under this study’s scenarios and 22% and 20% for medium and long trips, respectively. Estimated values for FC for the mild hybrid system were not given, but the main fuel savings was attributed to the start-stop system, which is dependent on idle time in the drive cycles. The battery and motor torque assist were estimated to lower FC by about 2%-3% regardless of the driving style. Because FC is reduced in all cases for the mild hybrid vehicle, the hybrid would be expected to be at least slightly more sensitive to driving style, but this hypothesis could not be quantified from the information in the paper.

Table 7. Model-estimated FC values for driving-cycle styles and trip length combinations for a compact conventional gasoline vehicle [13].

	FC, conventional vehicle (l/100 km)		
Drive cycle style	Short trip	Medium trip	Long trip
Calm	8.26	7.27	6.96
Normal	9.37	8.12	7.70
Aggressive	10.35	8.87	8.32
	FC change (%)		
Calm	base	base	base
Normal	13.4	11.7	10.7
Aggressive	25.4	22.1	19.6

ORNL Steady Speed Fuel Consumption Study

An ORNL study examined steady speed FE results from chassis dynamometer tests [5,14]. Data sets were collected for 23 vehicles at ORNL’s vehicle research laboratory, and (under a nondisclosure agreement) Chrysler Group, LLC (now Fiat Chrysler Automobiles), provided ORNL with data for another 51 vehicles tested at its Chelsea proving grounds. Combining the two data sets provided a base of 74 vehicles. The data considered are composed of FC for vehicles at steady speeds of 80.5, 96.6, 112.7, and 128.7 km/h (50, 60, 70, and 80 mph) [14].

The results are relevant to this study because driving fast is generally considered a form of aggressive driving. As seen in Table 8, traveling an additional 16.1 km/h (10 mph) faster will increase FC significantly (11%-21% in most cases) for virtually any vehicle, although the amount is vehicle dependent.

Table 8. Change in FC for vehicles traveling at steady speeds of 80.5 km/h and above [14]. Estimates are based on test data for 74 vehicles.

Speed increase	Relative FC increase accompanying each 16.1 km/h speed increase (%)		
	Average (%)	Data range (%)	Middle 75% of vehicle data (%)
80.5 to 96.6 km/h	14	7–22	11–18
96.6 to 112.7 km/h	16	10–24	12–20
112.7 to 128.7 km/h	18	12–35	14–21

MODEL AND EXPERIMENTS FOR AN HEV AND CONVENTIONAL GASOLINE VEHICLE MATCHED PAIR

It was desired to further explore the observation that HEVs experience proportionally greater FC change compared with conventional vehicles over various driving styles (see Figure 1 and related discussion). The authors hypothesized that HEV FC may be more sensitive to various levels of aggressive driving than conventional vehicle FC due largely to limitations of RB systems when considering drive cycles relevant to actual driving.

ORNL previously developed an analytical tool to examine vehicle energy [7,8]. A study by Rask et al. [16] measured limitations of RB systems, allowing such limitations to be added to the analytical tool. This combination formed a model that examines variation in tractive energy due to drive cycle intensity changes (in the same way as the Argonne studies [10,11,12]) and estimates RB system energy recovery and use. The variation in tractive energy due to drive cycle intensity is calculated for the vehicle, and the internal combustion engine (ICE) supplied tractive energy is estimated. Tractive energy may not be directly proportional to FC, but it does provide meaningful insight. Based on the model results it was deemed appropriate to perform a follow-on experimental investigation via vehicle testing in a chassis dynamometer laboratory.

Model for Engine-Supplied Tractive Effort Variation with Cycle Intensity

The modeling effort involved extending an existing spreadsheet calculation tool that examines specific vehicle drive-cycle energy requirements by adding an RB model. The specific HEV modeled was the 2011-2012 Hyundai Sonata HEV. The modeling effort that follows is not claimed to accurately simulate vehicle behavior but is intended to illustrate the major role RB can play in HEV energy consumption variability over differing drive cycles.

Drive-Cycle Energy Analysis Tool

A spreadsheet-based tool was previously developed [7] to examine energy use and dissipation using EPA test car database information [18]. This tool uses the EPA data results for standard test cycles, including the UDDS and HWFET cycles, and the Supplemental Federal Test Procedure cycle, known as the US06 cycle. (Other cycles can be examined if adequate input information is available). The US06 cycle represents aggressive driving relative to the UDDS and HWFET. From the standard drive traces and the EPA-provided data, cycle energy quantities can be calculated for each vehicle-cycle combination. The road load forces on the vehicle are integrated over the drive cycle to obtain results that include the total cycle tractive energy, braking energy, and combined drag energy. The physics have been explained previously [7,8,19], and a brief summary follows.

The tractive force, $\mathbf{F_{tr}}$, is considered only for positive values and is the force that the tires apply to the dynamometer roller drums (or road). Negative force generated by the vehicle is deemed as braking even if supplied in part by the powertrain (significant for hybrids). The braking force, $\mathbf{F_b}$, becomes nonzero when deceleration exceeds that provided by the (road-load) drag force, $\mathbf{F_d}$. The term "**Ma**" is the vehicle mass (and includes a rotating mass component), **M**, times the acceleration, **a**, forming the vehicle inertial term.

The forces integrated over distance generate work-energy values for drive cycles using $\int \mathbf{F} \cdot \mathbf{ds}$ (energy = force × distance), where **F** is a force and **ds** is an increment of distance. This allows calculation of the powertrain-provided tractive energy over a given drive cycle and the opposing cycle energy due to drag and braking losses. In summary, three drive cycle energy quantities can be calculated by

$$\sum F = Ma = F_{tr} - F_b - F_d \ , \tag{1}$$

$$\int F_{tr} \cdot ds = E_{tr} \ , \tag{2}$$

$$\int F_d \cdot ds = E_d \ , \tag{3}$$

and

$$\int F_b \cdot ds = E_b \ , \tag{4}$$

which allows comparisons of vehicle tractive energy requirements $\mathbf{E_{tr}}$, drag energy $\mathbf{E_d}$, and braking energy $\mathbf{E_b}$ over drive cycles.

Regenerative Braking System Limitations

Important limitations of RB systems have been described by Rask et al. [16]. Figure 7 is taken from Rask et al. and displays experimental data produced at Argonne's chassis dynamometer facility. This figure is quite useful for describing RB use and limitations and how the friction braking system is often "blended" with the RB system. The RB boundaries are described below and were used in the modeling effort.

Figure 7 gives braking force on the y-axis shown as a negative force (opposing forward vehicle motion) and the vehicle speed on the x-axis. The portion labeled A represents the ramping-out of the RB system that happens at low speeds. The regenerative brakes fade out, and if needed, the friction brakes do increasing work as the vehicle slows. The low energy and voltage becomes unfavorable for charging the battery, and below some finite vehicle speed only the friction brakes are used.

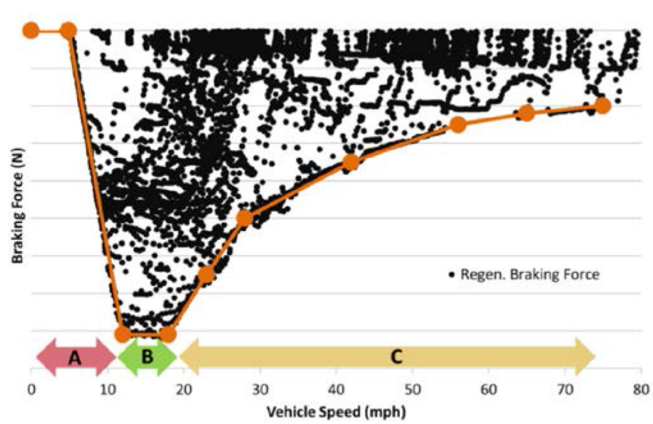

Figure 7. RB limitations (used by permission, Rask et al. [16]).

The B region is a zone where the maximum allowed RB force occurs. It is the region that can be defined by the maximum torque capability of a particular electric traction system, but in practice it is more likely a control limit to balance braking force between front and rear axles during hard braking for vehicle stability reasons. For many HEVs, the RB system uses the drive axle (generally the front axle) only. Controls ensure that under certain hard-braking conditions the proper balance of braking with both axles occurs [16].

Region C in Figure 7 is a power-based limitation. The limit could be determined by the traction drive power limit and/or a battery charging power limit [16].

Note that the three-region envelope depicted by Figure 7 is a somewhat idealized form of what can actually happen over the very wide variety of driving cycles and conditions that can be encountered. For example, the battery could become completely charged (consider coming down a mountain) and unable to use the RB system. The controls may protectively change battery charge capacity or charging rate due to high or low battery temperatures or other reasons. More discussion is found in Rask et al. [16] and Appendix B.

Model Inclusion of Regenerative Braking Limitations

The three-region concept for the limits of regenerative brakes was incorporated into the drive cycle energy analysis tool to compare energy use of a hybrid and a comparable conventional vehicle. This enabled estimation of the tractive energy requirements for selected drive cycles of a 2011-2012 Hyundai Sonata HEV and conventional Sonata vehicle. The variation in the tractive energy will be roughly proportional to FC assuming the powertrain efficiency is not changing significantly (an assumption that will only hold in some scenarios) over the cycles under consideration. Although this method does not explicitly estimate FE/FC, it will give estimates of the energy requirement variability over cycles for the vehicles.

Figures 8 and 9 are helpful for explaining the method further. Drive cycles consist of a set of discrete sequential time and vehicle speed point pairs defining the drive curve. The US06 drive curve shown in Figure 8 is used in this study as a basis to also form variant cycles described later. Braking force is calculated for all portions of a cycle that require braking and compared to the RB force limits as shown in Figure 9, where US06 cycle braking force (red points) values are seen grouped in short lines (actually a row of discrete points) representing a 1-second braking duration. Clearly many braking events are beyond the RB limit. (The red lines are an artifact of the discrete model. The US06 cycle is defined by a 1 Hz file, but a 10 Hz version is used to minimize integration errors. Many short red lines in Figure 9 are actually10 points representing a 1.0 s interval with a fixed deceleration rate; vehicle speed drops slightly and the braking force increases slightly to maintain the defined deceleration rate.)

The model assumes the rules stated below govern behavior to quantify regeneration. These are based on data and other information in [16] and [21]. The precise control details of the RB system are unknown.

1. When the braking force is less than or equal to the RB force limits defined in Figure 9, all braking is assumed to be accomplished by the RB system.
2. When the braking force is greater than the RB force limit, blended braking is used, with the RB system suppling braking force defined by the limit, and the remainder (beyond the limit) is supplied by friction braking.
3. A 70% efficiency is assumed for capturing RB energy and later returning that energy to the wheels for tractive power.

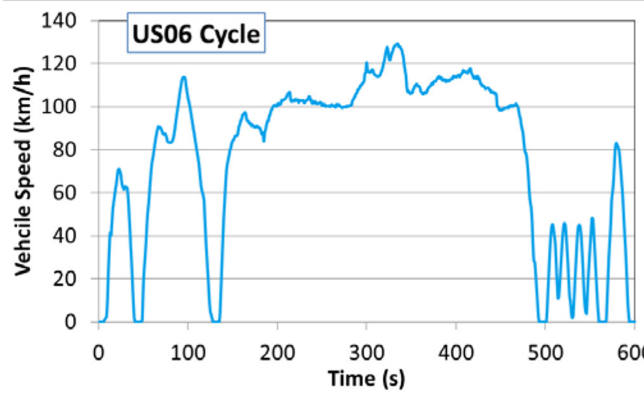

Figure 8. The US06 drive cycle represents relatively aggressive, but realistic, driving.

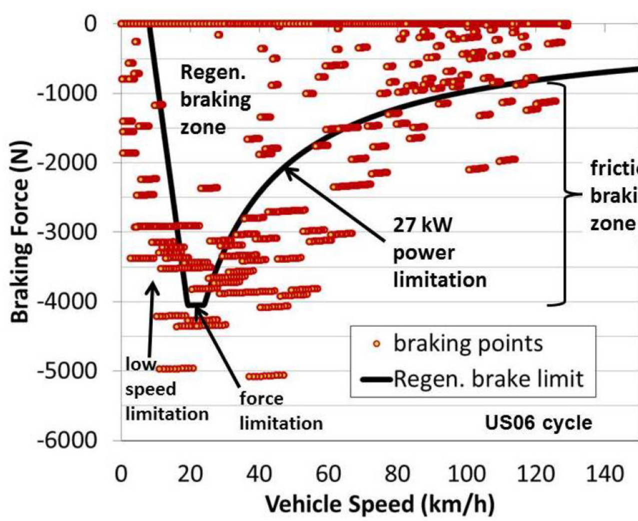

Figure 9. RB limits for a 2011 Sonata HEV and calculated brake force needed over the US06 cycle.

Vehicles and Cycles Considered

It was desirable to analyze an HEV with defined RB limitations that also had a “sibling” conventional vehicle so substantial similarity between the vehicles could be ensured. This was possible due to the characterization of the 2011 Hyundai Sonata HEV [16] and because Hyundai also markets a conventional Sonata with very similar features. Therefore a pair of Sonatas was chosen for this study.

Vehicles

A summary of the vehicles and attributes used in the modeling calculations follows. Note: EPA-listed data are identical for the 2011 and 2012 Sonata HEV, and similarly identical data are listed for 2011-2013 conventional (2.4 L, 190 hp) Sonata models.

(Also 2012) Hyundai Sonata HEV

2.4 L, 124 kW (166 hp) naturally aspirated Atkinson cycle engine; 6-speed automatic transmission; 30 kW electric motor; 1.4 kWh lithium-polymer battery pack

EPA 2011 and 2012 Database Data

Dynamometer target coefficients: A = 26.8 (lb), B = 0.15 (lb/mph), C = 0.0145 (lb/mph^2), Equivalent test weight (ETW): 3,750 lb

(Also 2012 and 2013) Hyundai Sonata (Conventional Gasoline Vehicle)

2.4 L, 142 kW (190 hp) naturally aspirated engine; 6-speed automatic transmission

EPA 2011-2013 Database Data

Dynamometer target coefficients: A = 29.45 (lb), B = 0.5673 (lb/mph), C = 0.0101 (lb/mph^2), ETW: 3,500 lb

Road load at a given vehicle speed (velocity) V is calculated as force = $(A + BV + CV^2) + Ma$, where A, B, C, V, M and a are in appropriate units. The EPA database uses imperial units with V measured in mph, A in lb, B in lb/mph and C in lb/mph^2, and the product of mass times acceleration (Ma) in lb. Our calculations are based on these values.

The resultant drag-related road loads calculated from the target coefficients are shown in Figure 10. The drag-related road load is similar for the two vehicles, with the HEV having somewhat lower drag-related road load compared to the conventional Sonata despite the HEV having greater mass.

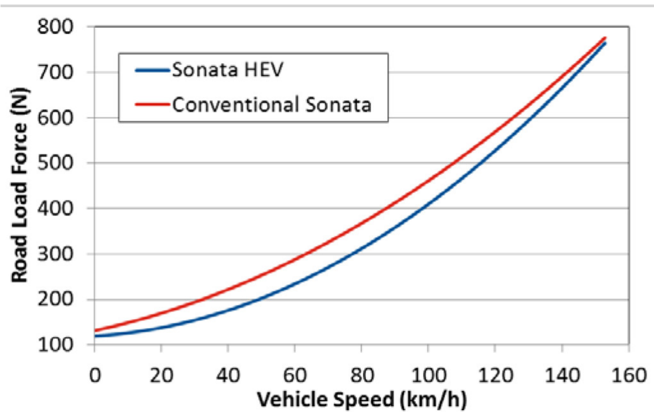

Figure 10. Road-load force curves for the 2011 Hyundai Sonata hybrid and conventional vehicles.

US06 Cycle and Intensity Scaling

The US06 cycle was chosen as a basic cycle because it is a standard EPA cycle featuring significantly more aggressive driving than the UDDS or HWFET cycles. These latter cycles have low values of maximum acceleration and deceleration while in comparison the US06 maximum rates are more than double those of the UDDS or HWFET cycles (Appendix A). Cycle intensity was varied following the method of Carlson et al. [12], allowing significant changes to the cycle aggressiveness while preserving the distance traveled for each cycle. To change a cycle's intensity a scaling factor is used as a multiplier of the speed at all points while the drive trace time is inversely scaled. For the study we examined scaling factors of 0.8, 0.9, 1.0, and 1.1 as a means of exploring a wide but reasonable range of driving aggressiveness or style. An example of scaling the US06 cycle is shown in Figure 11.

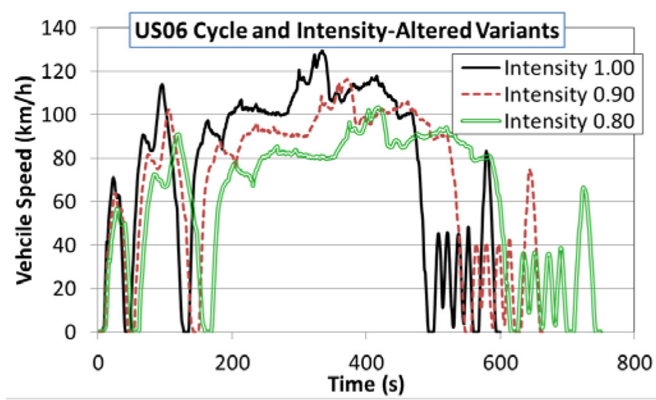

Figure 11. The US06 cycle can be modified in intensity to form variants with lower or higher speeds and rates of accelerations and decelerations.

US06 City Cycle

EPA defined the city portion of the US06 cycle [20] as the more severe acceleration/deceleration portions of the US06: specifically the initial two "hills" (0 to 131 s) and the final "hills" (496 to 600 s), as illustrated in Figure 12. This creates the US06 City cycle, which is a relatively aggressive 235-second drive cycle shown in Figure 13.

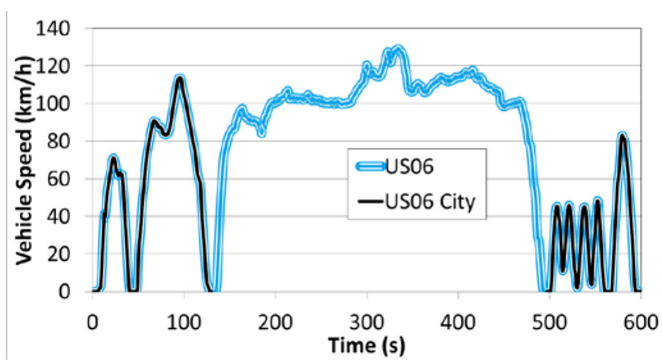

Figure 12. The US06 City cycle is represented by the two portions of the US06 trace shown in black. The US06 City cycle retains much of the hard accelerations and decelerations of the US06.

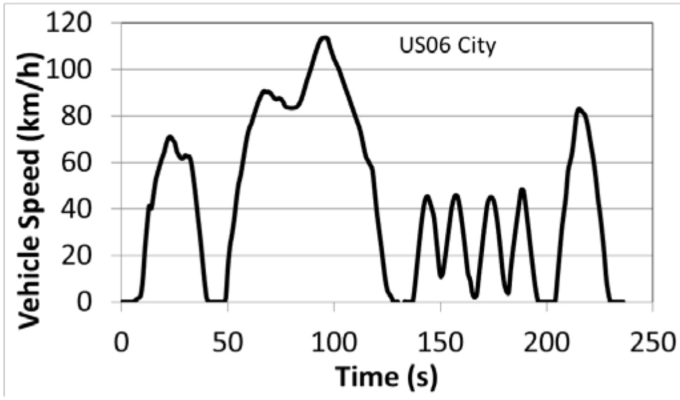

Figure 13. The US06 City cycle is shown here as one continuous cycle.

Model Results for Varying Cycle Intensity

Energy requirements were calculated for the HEV and conventional Sonata models over the US06 and US06 City cycles and their respective variants altered to different intensity levels. Detailed results given in Tables 9 and 10 and Figures 14 and 15 show normalized ICE powertrain-supplied tractive energy using the 0.8 intensity cycles as the base cases. Very little friction braking is needed for the HEV over the 0.8 intensity cycles, but this increases in a very nonlinear way with increasing cycle intensity (Tables 9 and 10). The percent increase for ICE-supplied tractive energy is larger for the HEV compared to the conventional vehicle for increasing cycle intensity, but the absolute ICE-supplied tractive energy required (kJ/km) actually increases more for the conventional vehicle. This is true for both the US06 and the US06 City cycle series.

Table 9. Model results varying cycle intensity using the US06 cycle as the base cycle.

US06-based cycle model results				
Cycle intensity (1.0 = standard cycle)	0.80	0.90	1.00	1.10
Total test time (s)	750	667	600	546
Average vehicle velocity (km/h)	61.9	69.6	77.3	85.1
Test distance (km)	12.89	12.89	12.89	12.89
Conventional Sonata results				
Tractive energy (kJ/km)	480.3	564.7	657.9	760.1
Friction brake energy (kJ/km)	116.3	156.0	201.1	251.6
Increase in ICE supplied energy (%)	0.0	17.6	37.0	58.2
Sonata HEV results				
Tractive energy (kJ/km)	448.7	538.8	639.3	750.4
Friction brake energy (kJ/km)	5.6	17.3	47.9	96.1
Regenerative brake energy (kJ/km)	132.5	164.5	183.3	190.0
Electrically powered tractive energy (70% of RB energy) (kJ/km)	92.8	115.2	128.3	133.0
ICE powered tractive energy (kJ/km)	355.9	423.5	511.0	617.4
Increase in ICE supplied energy (%)	0.0	19.0	43.6	73.5

Table 10. Model results varying cycle intensity using the US06 City cycle as the base cycle.

US06 City–based cycle model results				
Cycle Intensity (1.0 = standard cycle)	0.80	0.90	1.00	1.10
Total test time (s)	293.8	261.1	235.0	213.6
Average vehicle velocity (km/h)	35.0	39.3	43.7	48.1
Test distance (km)	2.852	2.852	2.852	2.852
Conventional Sonata results				
Tractive energy (kJ/km)	634.4	775.0	932.0	1105
Friction brake energy (kJ/km)	350.5	463.0	589.9	730.7
Increase in ICE supplied energy (%)	0.0	22.2	46.9	74.1
Sonata HEV results				
Tractive energy (kJ/km)	638.7	788.4	955.8	1141
Friction brake energy (kJ/km)	19.6	49.4	128.8	268.0
Regenerative brake energy (kJ/km)	384.8	477.4	535.3	547.9
Electrically powered tractive energy (70% of RB energy) (kJ/km)	269.3	334.2	374.7	383.5
ICE powered tractive energy (kJ/km)	369.3	454.2	581.1	757.1
Increase in ICE supplied energy (%)	0.0	23.0	57.3	105.0

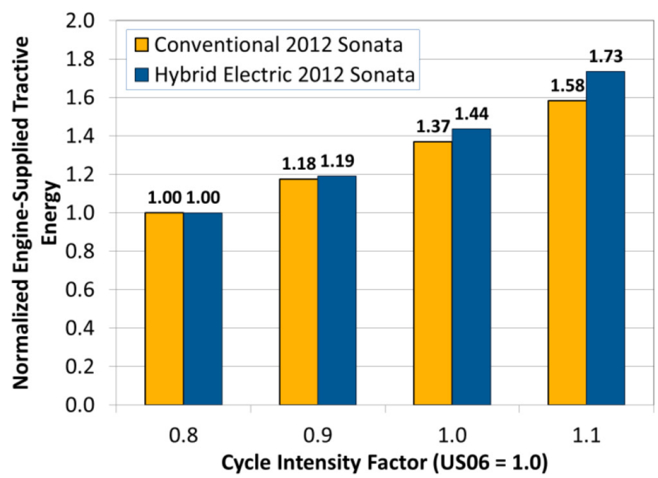

Figure 14. Normalized engine-supplied tractive energy as a function of US06-based drive cycles.

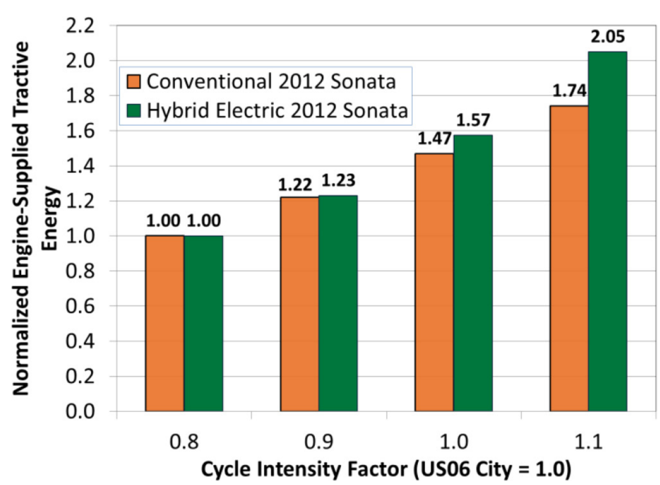

Figure 15. Normalized engine-supplied tractive energy as a function of US06 City-based drive cycle.

These results give support to the hypotheses that for the cycles studied (1) HEV FC is more sensitive to various levels of aggressive driving than conventional vehicle FC and (2) a major cause is RB system limitations. Because the simple vehicle energy model has significant limitations and because only one pair of vehicles was examined over two sets of cycles, caution must be exercised in making any generalized conclusions from the model results. The model quantifies how tractive energy increases with cycle intensity (which is a straightforward calculation [7]), and has a simple method of estimating RB energy capture and subsequent use to power the vehicle. Not included are how the ICE powertrain and electric powertrain efficiencies will change somewhat for various drive cycles and how other vehicle factors may affect FC.

The 70% RB efficiency assumption is an estimate based on (1) measured energy flows for a Nissan Leaf [21,22] over the UDDS cycle which reveal a RB system efficiency (brakes-to-battery and battery back to wheels) slightly above 70% and (2) information on the Chevrolet Volt powertrain [23] that shows an 84% efficiency for only RB charging of the battery over the US06 cycle (more losses will be incurred returning battery energy to power the wheels). The 70% estimated efficiency represents energy losses from the tires, the electric motor-generator, any mechanical friction, the power conditioning electronics package, and the battery charging event and then reversing the energy flow with losses for battery discharge, power conditioning, electric motor powering, mechanical systems, and the tires. A sensitivity analysis using efficiency values of 60% or 80% did not change the basic trends supporting the premise that RB limitations are a major reason for higher FC change for an HEV compared to a conventional vehicle over the cycles examined. It would be interesting to examine how RB energy efficiency actually changes with drive cycle, but this was beyond the scope of the current study.

The ICE-supplied tractive energy trends may differ from the trends in FC because the engine and transmission efficiencies will change somewhat with the cycles. If the efficiency changes are small, the trends for tractive energy and FC will be similar. An experimental campaign mimicking this simple modeling exercise was performed and is described in the next section.

Vehicle Dynamometer Experiments

The trends from the model results, while interesting, could be more compelling if validated by vehicle experiments. Vehicle testing was pursued using a chassis dynamometer laboratory and the same cycles and vehicle types studied by modeling.

Vehicles and Laboratory

Vehicle experiments were performed at ORNL's Fuels, Engines, and Emissions Research Center. The vehicle research laboratory features a Burke E. Porter 224 kW (300 hp) motor-in-the-middle, two-wheel drive, 1.89 m (48 in.), single roll AC motoring chassis dynamometer. Gaseous vehicle emissions are measured with conventional gas analyzers sampling from a constant volume sampling (CVS) system (dilution tunnel) and the CVS bag sampling system. Reported results for FC were derived from measurements using an Emerson Micro Motion CMF010M, Coriolis-effect flow and density meter to measure instantaneous and cumulative FC. FC and CO_2 emission levels also can be derived from the integrated emissions sampled from the CVS dilution tunnel using the carbon mass balance method specified by EPA and Code of Federal Regulations guidelines. Coriolis-based FC and carbon mass balance FC generally agree to within 2%.

The vehicles used for the experiments are described below.

2012 Hyundai Sonata HEV

2.4 L, 166 hp naturally aspirated Atkinson cycle engine; 6-speed transmission; 30 kW electric motor; 1.4 kWh battery pack

2012 Hyundai Sonata Conventional Gasoline Vehicle

2.4 L, 190 hp naturally aspirated direct-injected gasoline engine; 6-speed transmission

The vehicle attributes, target coefficients, and test weights were identical to those used for the modeling exercise. Furthermore, Argonne used the same target coefficients and ETW for the 2011 Sonata HEV experimental work mentioned previously [16].

Drive Cycles

The drive cycles used for the vehicle experiments were the same as those described in the previous section on modeling. The conventional vehicle was operated over the cycles in the sequences shown in Figures 16 and 17, with the intensity scaling factors in the order 1.0, 0.9, 1.1, and 0.8. As shown in Figure 17, the US06 City-based cycles were driven as double-cycles (two identical consecutive cycles) to create a cycle length closer to the US06-based cycles and to improve the accuracy of the data. All experiments began with the vehicles in the same prescribed fully-warmed state.

Conventional Vehicle Experiments

For the conventional Sonata, each test cycle sequence was run in triplicate. Results gave consistent FC values. The list below explains more about the experiments.

1. A nominally 10% ethanol, 30.61 MJ/L lower heating value commercially available retail gasoline was used.
2. The vehicle was driven in a warm-up phase to achieve engine oil temperature near 95°C before the cycle tests began.
3. The four types of cycles were driven as a single test as shown in Figures 16 and 17, with the idle periods shown separating the cycle types. Tests were repeated 3 times.
4. Oil temperature was observed to remain between 95°C and 104°C for all US06-based tests and between 95°C and 108°C for all US06 City-based tests (oil temperature was not a significant factor affecting FC variation).

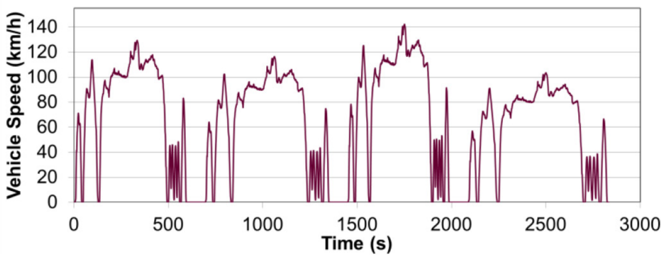

Figure 16. US06-based cycles are shown in the experimental sequence used for the conventional vehicle with intensity scaling factors of 1.0, 0.9, 1.1, and 0.8, respectively.

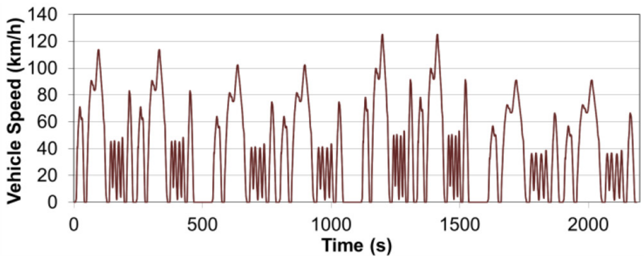

Figure 17. US06 City-based cycles are shown in the experimental sequence used for the conventional vehicle with intensity scaling factors of 1.0, 0.9, 1.1, and 0.8, respectively. The sequence features pairs of identical cycles to create a longer drive length for each condition.

Hybrid Vehicle Experiments

The experimental methods for testing the vehicles differed between the HEV and conventional vehicle because the battery state of charge (SOC) for the HEV can impact FC. In consideration of the SOC, several identical cycles were repeated, to find a group of cycles that started and ended near the same SOC value.

1. The same 10% ethanol gasoline used in the conventional vehicle experiments was used.
2. The vehicle was driven in a warm-up phase to achieve engine oil temperature near 95°C before beginning the cycle tests.
3. A single cycle type was driven repeatedly due to battery SOC concerns. The US06-based cycles were repeated 4 times per test, and the US06 City-based cycles were repeated 6 times per test. All tests were repeated 3 times.
4. Oil temperature was observed to remain between 90°C and 115°C for all testing.

The battery SOC was monitored (from an appropriate OBD-II data channel and secondarily by using a Hioki 3390 Power Analyzer) and typically changed over each individual drive cycle. Because the tests were performed in triplicate, data were generated for 12 US06 cycles and for each variant and for 18 US06 City cycles and each variant. Groups of cycles were chosen that when combined had a low net change in SOC (0% to 2% net SOC change). An OBD-II channel output was found to correlate with the measured percentage change in battery SOC. Furthermore, a 1% change in SOC was estimated to be equivalent to about 3 g of fuel consumed, a very small amount compared to cycle fuel consumed (FC results are based on totals of about 1,150 g to 4,000 g of fuel consumed). Details concerning how variation in battery SOC was considered are given in Appendix C.

Experimental Results

Detailed results are given in Tables 11 and 12, with the FC results depicted in Figures 18 and 19. A large increase in FC with cycle intensity is clearly quantified as is the greater fractional FC change for the HEV. Figures 20 and 21 show FC normalized to the 0.8 scaling factor cycles, which highlights the relative change in FC for each vehicle as the cycles are intensified. Both plots reveal that increasing the cycle intensity has a greater impact on FC for the HEV compared to the conventional vehicle. However, the US06 City-based cycles give a greater difference between the intensity effects for the HEV and conventional vehicle. The original intent when including the US06 City cycle and variants was to examine the effects of cycles with a relatively large amount of hard braking to magnify the RB effects.

The experimental FC results have similarities to the model results for tractive energy, and together they appear to support the RB limitations hypothesis. However, a more sophisticated experimental study that includes monitoring the energy flows of the RB and battery and electric motor systems is needed to definitively quantify the role of RB in the FC results.

Table 11. Experimental results for the US06 cycle series.

US06-based cycle experimental results				
Cycle intensity (1.0 = standard cycle)	0.80	0.90	1.00	1.10
Total test time (s)	750	667	600	546
Test distance (km)	12.89	12.89	12.89	12.89
Conventional Sonata results				
Tractive energy (kJ/km)	480.3	564.7	657.9	760.1
Number of cycles included	3	3	3	3
Fuel consumption (l/100 km)	6.18	7.17	8.59	9.55
Fuel consumption increase (%)	0.0	15.9	38.9	54.5
Vehicle efficiency (%)	25.4	25.7	25.0	26.0
Sonata HEV results				
Tractive energy (kJ/km)	448.7	538.8	639.3	750.4
Number of cycles included	4	8	6	4
Net SOC change over cycles (%)	-1	-1	0	-1
Fuel consumption (l/100 km)	4.44	5.22	6.36	7.77
Fuel consumption increase (%)	0.0	17.6	43.0	75.0
Vehicle efficiency (%)	33.0	33.7	32.9	31.5

Table 12. Experimental results for the US06 City cycle series.

US06-city–based cycle experimental results				
Cycle Intensity (1.0 = standard cycle)	0.80	0.90	1.00	1.10
Total test time (s)	293.8	261.1	235.0	213.6
Test distance (km)	2.852	2.852	2.852	2.852
Conventional Sonata results				
Tractive energy (kJ/km)	634.6	775.2	932.0	1105
Number of cycles included	4	4	4	4
Fuel consumption (l/100 km)	9.81	11.50	13.95	16.29
Fuel consumption increase (%)	0.0	17.2	42.2	66.0
Vehicle efficiency (%)	21.1	22.0	21.8	22.2
Sonata HEV results				
Tractive energy (kJ/km)	638.8	788.6	955.8	1141
Number of cycles included	10	9	16	9
Net SOC change over cycles (%)	0	0	-2	-2
Fuel consumption (l/100 km)	5.65	6.84	8.62	11.64
Fuel consumption increase (%)	0.0	21.1	52.7	106.1
Vehicle efficiency (%)	37.0	37.7	36.2	32.0

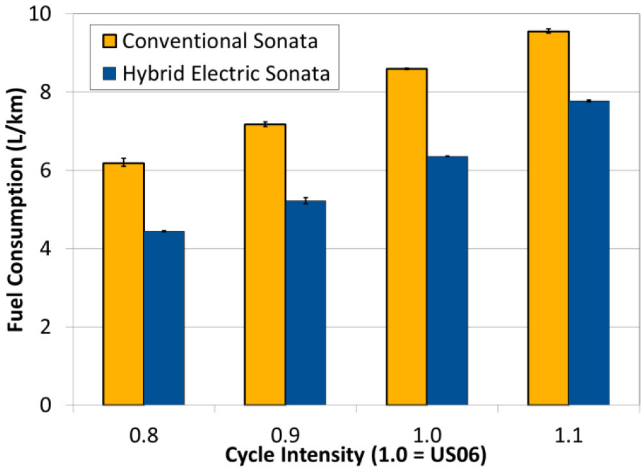

Figure 18. Experimental FC results for the conventional and hybrid Hyundai Sonatas as a function of US06-based cycles with altered intensity levels.

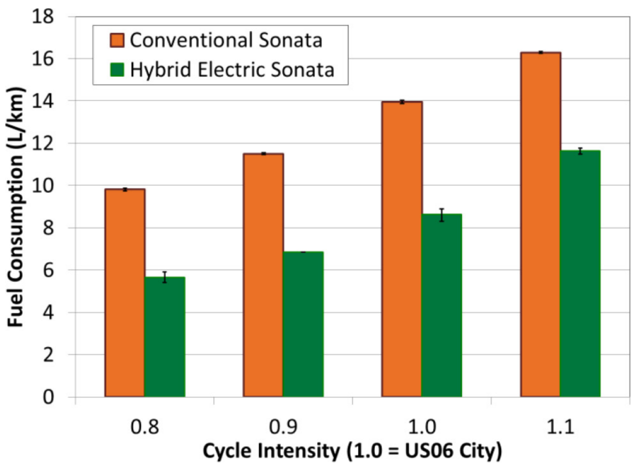

Figure 19. Experimental FC results for the conventional and hybrid Hyundai Sonatas as a function of US06 City-based cycles with altered intensity levels.

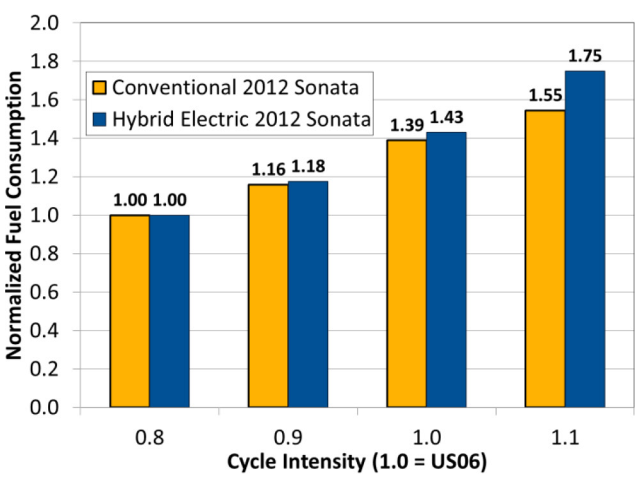

Figure 20. Normalized FC results for the conventional and hybrid Hyundai Sonatas as a function of US06-based cycles with altered intensity levels.

Note FC data range bars are included in Figures 18 and 19. For the conventional vehicle this is simply the range in FC from the three experiments performed for each cycle. For the HEV, it is the range of the FC values of the chosen consecutive-cycle groups from each experiment that were added together in a fashion to keep net SOC changes to a minimum. Generally each of the chosen consecutive cycle groups had only small SOC changes from start to finish, but there were two exceptions. For the 0.9 intensity US06 cycle experiments, the cycle groups had SOC changes of 4% and -5% (adding to achieve the -1% reported in Table 11), and groups for the 1.0 intensity US06 City cycle had SOC changes of -1%, -11% and 10%. The range bars are generally somewhat larger in these cases (as would be expected) than for the other results.

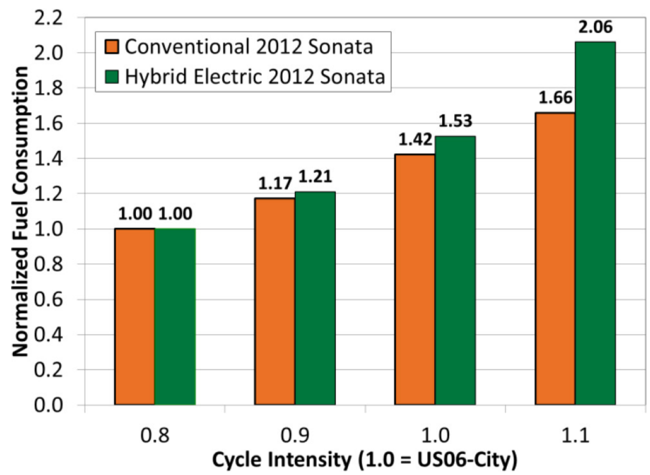

Figure 21. Normalized FC results for the conventional and hybrid Hyundai Sonatas as a function of US06 City-based cycles with altered intensity levels.

CYCLE ANALYSIS OF AGGRESSIVE DRIVING STUDIES

Known attributes of the cycles considered are compiled in Appendix A, Table A1, which lists average acceleration, peak acceleration and deceleration, and average cycle speed. Observations can be made from Figures 22 and 23, which plot cycle average speed versus acceleration and peak acceleration. In the Lenaers study [9], peak acceleration was unavailable, and because average acceleration was given as a range, the range midpoints were used for Figure 23 (which shows the urban and rural routes only; not enough is known about the motorway route to plot points but the speeds were 100-106 km/h and would have low average acceleration values). No attributes are available for the study by Liu et al. [13], which examined a broad array of cycles and used a more complicated method for defining driving aggressiveness.

The following are some noteworthy observations from Table A1 and Figures 22 and 23.

- The cycle sets examined are different in each study, although both Duoba [10] and Carlson[12] use the UDDS as a base case cycle.
- The HWFET cycles and variants in Duoba [10] feature low average acceleration values and progress to high average speeds. Aerodynamic drag will be a dominant factor for this cycle sequence.
- The ORNL study features cycles with significantly greater peak acceleration and deceleration values compared to the other studies [10,12], although the Lenaers [9] study values are unknown.
- The US06 City cycles and variants progress to the highest average acceleration/deceleration values.

- The ORNL study explores cycles that are significantly more severe (aggressive) in terms of acceleration/deceleration compared to the Argonne studies [10,11,12].

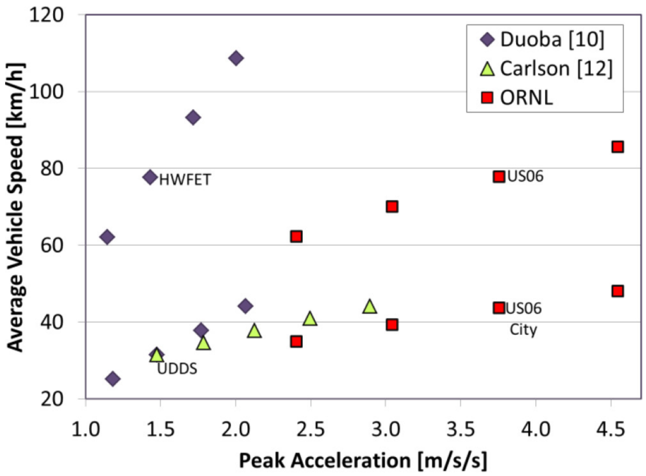

Figure 22. Comparison of studied drive cycles using average vehicle speed and maximum acceleration as metrics.

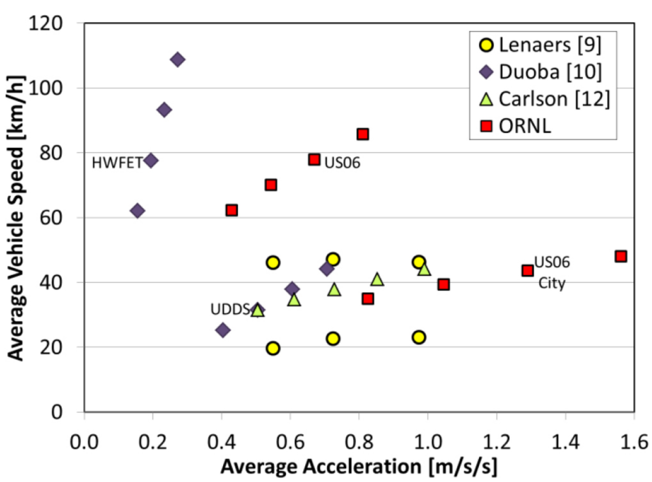

Figure 23. Comparison of drive cycles using average vehicle speed and average acceleration as metrics.

VEHICLE EFFICIENCY CONSIDERATIONS

It is useful to plot vehicle energy in terms of the required tractive energy over a cycle versus the fuel used for the cycle. The ratio of tractive energy requirements, $\mathbf{E_{tr}}$, [see Eq. (2)] to the fuel energy, $\mathbf{E_{fuel}}$, is the vehicle efficiency, $\boldsymbol{\eta_{tr}}$, over the given cycle.

$$\boldsymbol{\eta_{tr}} = \mathbf{E_{tr}} / \mathbf{E_{fuel}} \tag{5}$$

The ORNL results are plotted in Figure 24 along with lines of constant efficiency. The conventional vehicle maintains a relatively constant or slightly improving efficiency over both the US06- and the US06 City-based cycles. The higher efficiencies for the US06-based cycles is likely due to favorable engine load levels during the long cruising part of the cycles, allowing operation at relatively high efficiency portions of the engine map. The US06 City cycle is a very stop-and-go type cycle with hard braking likely negating much of the engine efficiency improvements with intensity increase.

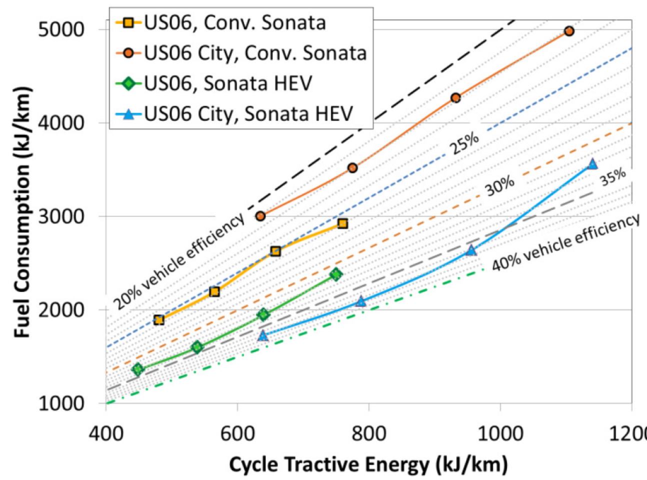

Figure 24. Fuel energy as a function of tractive energy for the conventional and hybrid Hyundai Sonatas over intensity modified US06 and US06 City cycles.

The Sonata HEV shows different behavior, with efficiency improving very slightly and then degrading with cycle intensity for both cycle types. This result is consistent with the contention that the use of friction braking increases in a nonlinear fashion with cycle intensity, diminishing the proportion of RB energy. It is also interesting to see the high efficiency of the HEV over the US06 City-based cycles due to high RB energy capture.

It was possible to apply this same type of analysis to the six vehicles featured in the Argonne study [10] that listed the A, B, and C, coefficients and ETW for each vehicle (studied vehicles: Toyota Prius, Honda Insight, Ford Focus, Toyota Echo, Ford Escape, Jaguar XJ8). Figure 25 gives results for the UDDS-based cycles. These cycles have much lower acceleration/deceleration and speeds compared to the ORNL study. The conventional vehicles show large changes in efficiency over the cycles (factors of ~1.5-1.7), with engine load being the dominating factor. The Insight has a somewhat lower swing in efficiency than the conventional vehicles (~1.4 factor). The Prius is quite different, showing high efficiency for the 1.0 and 1.2 speed multiplied cycles and lower values for the 0.8 and 1.4 multiplier cases.

The behavior of efficiency improving and then degrading with cycle intensity seen for the 2004 Prius (Figure 25) could not be directly investigated by using the ORNL model due to lack of specific RB system limitation data. However, 2010 Prius information was available from Rask [16] and could be modeled. A significant increase in friction braking is required for the 1.4 speed multiplied UDDS cycle (significant braking is beyond the RB limits) compared to the 1.2 multiplier cycle and the lower intensity cycles. This accounts for some of the change in efficiency seen in Figure 25; however, the effect appears less significant than for the ORNL test cycles and depends on the assumption that the 2004 and 2010 Priuses have relevant similarities. The Prius powertrain is complicated and has reasons in addition to RB limitations for efficiency changes according to Duoba et al. [10].

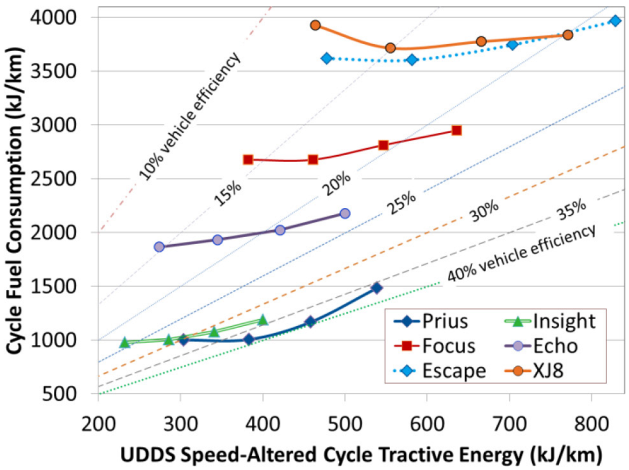

Figure 25. Fuel energy as a function of tractive energy for six vehicles for speed multiplied UDDS cycles in [10] (speed multipliers are 0.8, 1.0, 1.2, and 1.4).

CONCLUSIONS

Despite the lack of an objective definition of aggressive driving, a number of studies have made efforts to quantify fuel consumption (FC) penalties associated with aggressive driving styles. These studies associated aggressiveness with higher levels of acceleration and braking, and most included higher speeds as well. Some studies examined a range of driving cycles to address the large range of driving conditions incurred in actual driving. Conclusions addressing the significant fuel use penalties estimated for aggressive driving follow. Also addressed is the fact that HEVs respond somewhat differently to driving style compared to conventional powertrain vehicles. However, the following caveats should be noted; the modeling included simplifications (which is normal for models), and in addition most vehicles examined in the studies were sedans and only a limited number of HEVs were studied.

Aggressive driving was found to have a large effect on FC for urban low speed driving cycles. The bulk of the results showed FC increases of 25% to 68% for aggressive driving versus mild to normal driving. Comparisons between highly aggressive and mild driving resulted in FC increases of greater than 100%.

Results pertaining to moderate speed highway type driving with some traffic controls (as opposed to high speed limited access roads known as motorways or interstate highways) generally indicated a FC increase in the range of 20% to 46% for conventional vehicles and slightly higher values for HEVs.

Relevant studies for urban and highway driving indicated HEVs can have more FC sensitivity to driving style, on a percent basis, than similar conventional vehicles. However, the same results also indicate that in absolute FC terms, the HEVs generally experience a lower or similar FC penalty compared to conventional vehicles. The modestly higher HEV percent sensitivity is consistent with the limitations and functionality of regenerative braking systems.

Results applicable to limited access motorway driving revealed fuel use penalties of 5%-14% for aggressive driving (accelerating hard when there is opportunity) when speed limits were obeyed. Increased speeds of 16 km/h (10 mph) in the speed range of 80-130 km/h (50- 80 mph) usually results in 11%-21% increased FC. These two types of aggressiveness, one by harder accelerations and the other by higher speed driving, are additive.

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ACKNOWLEDGMENTS

This report and the work described were sponsored by the DOE Office of Energy Efficiency and Renewable Energy (EERE), Vehicle Technologies Office (VTO). The authors gratefully acknowledge the support of Dennis Smith, VTO and the Fuel Economy Information Project under the Clean Cities program. The programmatic guidance of Bo Saulsbury at ORNL is also gratefully acknowledged. A portion of this work used resources of the National Transportation Research Center, an EERE User Facility operated by ORNL. Excellent laboratory work was performed by our professional vehicle driver Larry Moore. The authors acknowledge the expansive vehicle research and characterization work and cooperation of Argonne researchers, particularly Henning Lohse-Bush, Mike Duoba, Eric Rask, and Theodore Bohn. Finally, we gratefully acknowledge the dedication of VJ Ewing at ORNL and the anonymous peer reviewers and SAE editors for their assistance with improving this publication.

DEFINITIONS/ABBREVIATIONS

Argonne - Argonne National Laboratory

CVS - constant volume sampling

DOE - US Department of Energy

EPA - US Environmental Protection Agency

ETW - equivalent test weight (usually reported in pounds)

FC - fuel consumption (fuel use/distance)

FE - fuel economy (distance/fuel use)

GHG - greenhouse gas

HEV - hybrid electric vehicle

HWFET - Highway Fuel Economy Test (schedule, US EPA)

ICAR - International Center for Automotive Research (Clemson University)

ICE - internal combustion engine

LPG - liquefied petroleum gas

MATT - Modular Automotive Technology Testbed

MY - model year

NHTSA - National Highway Traffic Safety Administration

ORNL - Oak Ridge National Laboratory

PHEV - plug-in hybrid electric vehicle

RB - regenerative braking

SOC - state of charge (HEV battery)

UDDS - Urban Dynamometer Drive Schedule

APPENDIX

APPENDIX A. COMPARISON OF DRIVE CYCLE ATTRIBUTES

Selected attributes of drive cycles examined are tabulated in Table A1.

Table A1. Comparison of speed and acceleration for various drive cycles

	Cycle attributes			
Cycle description	**Average acceleration (m/s/s)**	**Peak acceleration (m/s/s)**	**Average cycle speed (km/h)**	**Peak deceleration (m/s/s)**
Lenaers, 2007 [9]				
Normal urban	0.65–0.80	—	20–25	—
Aggressive urban	0.85–1.10	—	22–26	—
Normal rural	0.65–0.80	—	45–50	—
Aggressive rural	0.85–1.10	—	44-50	—
Normal motorway	—	—	102–106	—
Aggressive motorway	—	—	100–104	—
Duoba et al., 2007 [10]				
Speed × 0.8 UDDS	0.404	1.18	25.3	1.18
UDDS	0.505	1.48	31.6	1.48
Speed × 1.2 UDDS	0.605	1.77	37.9	1.77
Speed × 1.4 UDDS	0.706	2.07	44.2	2.07
Speed × 0.8 HWFET	0.155	1.14	62.2	1.18
HWFET	0.194	1.43	77.7	1.48
Speed × 1.2 HWFET	0.233	1.72	93.2	1.77
Speed × 1.4 HWFET	0.272	2.00	108.8	2.07
Carlson et al., 2009 [12]				
UDDS	0.505	1.48	31.6	1.48
Intensity × 1.1 UDDS	0.611	1.78	34.8	1.78
Intensity × 1.2 UDDS	0.727	2.12	37.9	2.12
Intensity × 1.3 UDDS	0.853	2.49	41.1	2.49
Intensity × 1.4 UDDS	0.989	2.89	44.2	2.89
ORNL, 2016				
Intensity × 0.8 US06	0.429	2.40	62.3	1.98
Intensity × 0.9 US06	0.543	3.04	70.1	2.50
US06	0.670	3.76	77.9	3.08
Intensity × 1.1 US06	0.811	4.54	70.1	3.73
Intensity × 0.8 US06 City	0.83	2.40	35.0	1.92
Intensity × 0.9 US06 City	1.05	3.04	39.3	2.43
US06 City	1.290	3.76	43.7	3.00
Intensity × 1.1 US06 City	1.56	4.54	48.1	3.62

APPENDIX B. EXAMPLE OF THERMAL EFFECTS ON BATTERY CAPACITY

Data in Figure B1 were taken from an instrumented 2010 Toyota Prius and 2012 Prius plug-in hybrid electric vehicle (PHEV) driven over the US06 cycles in Argonne National Laboratory's (Argonne's) vehicle laboratory [22,24]. The regenerative braking (RB) force is the y-axis value shown as a negative force (opposing vehicle motion) plotted against vehicle speed (see discussions of Figures 7 and 9).

The green and red points were obtained while running two consecutive US06 cycles with the 2010 Prius, with the green point generated over the first cycle. When the second cycle was driven, the envelope for RB shrank, most likely due to purposeful calibrations for thermal protection of the battery. During the first cycle, the battery became hot from charging and discharging and so less charging and discharging was allowed during the second US06 to prevent battery over-heating. A larger RB envelope is seen for the 2012 PHEV Prius, which has a much larger battery pack.

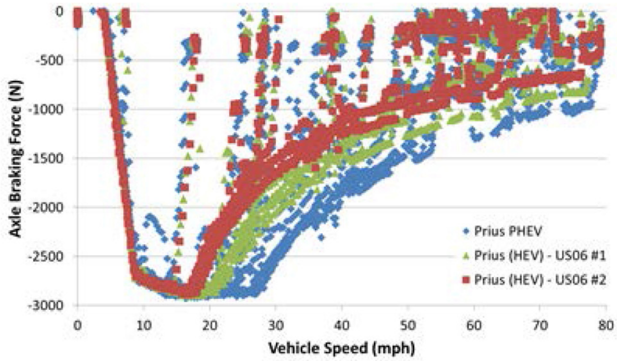

Figure B1. RB force over two consecutive US06 cycles (green and red points) for a 2010 Toyota Prius. Data are also shown for a 2012 Prius PHEV. Figure is courtesy of Argonne [22, 24].

APPENDIX C. HEV BATTERY SOC TRACKING METHODS

There were two methods for determining battery state of charge (SOC) and changes to SOC during the Oak Ridge National Laboratory experiments using the 2012 Sonata hybrid electric vehicle. A previous effort to monitor OBD-II signals found a channel that correlated to percent SOC (hexadecimal numbers spanning 60 to 160) when compared to the vehicle's dash readout. A second method was used monitoring the battery input/output voltage and current to obtain net energy change using a Hioki 3390 Power Analyzer. Using both methods and correlating the data gave an estimate of 1% SOC change, representing about ~ 0.007 kWh = 25 kJ. The battery rating is 5.3 Ah, 1.4 kWh [25], and 100% change in SOC would be roughly 0.7 kWh or ½ the battery rated capacity. Values in SOC observed from all experiments (including those not presented in this paper) spanned 39% to 99%. This would appear to be reasonable based on common reports that less than 50% of the actual battery capacity is used in application.

A 1% change in SOC was estimated to be 25 kJ, and the fuel used contains about 41.1 kJ/g energy per mass based on lower heating value. Therefore a 1% change in SOC represents engine fuel consumption of about 3 g assuming a 20% engine and electric generating efficiency.