The Measured Impact of Vehicle Mass on Road Load Forces and Energy Consumption for a BEV, HEV, and ICE Vehicle

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ABSTRACT

The U.S. Department of Energy's Office of Energy Efficiency & Renewable Energy initiated a study that conducted coastdown testing and chassis dynamometer testing of three vehicles, each at multiple test weights, in an effort to determine the impact of a vehicle's mass on road load force and energy consumption. The testing and analysis also investigated the sensitivity of the vehicle's powertrain architecture (i.e., conventional internal combustion powertrain, hybrid electric, or all-electric) on the magnitude of the impact of vehicle mass. The three vehicles used in testing are a 2012 Ford Fusion V6, a 2012 Ford Fusion Hybrid, and a 2011 Nissan Leaf. Testing included coastdown testing on a test track to determine the drag forces and road load at each test weight for each vehicle. Many quality measures were used to ensure only mass variations impact the road load measurements. Chassis dynamometer testing was conducted over standard drive cycles on each vehicle at multiple test weights to determine the fuel consumption or electrical energy consumption impact caused by change in vehicle mass. The road load measurements obtained from the coastdown testing were used to configure the chassis dynamometer. Chassis dynamometer testing also incorporated many quality controls to ensure accurate results.

The results of the testing and analysis showed that for a given vehicle, the road load shows a slightly non-linear trend of decreasing road load with decreasing mass. This trend appears to be consistent across vehicle powertrain architectures (i.e., conventional powertrain, hybrid electric, or all-electric). Chassis dynamometer testing of fuel consumption or electrical energy consumption showed for the Highway Fuel Economy Test drive cycle there was little impact due to change in mass for all three vehicles. For the Urban Dynamometer Drive Schedule and US06 drive cycle, there was a 2.4 to 4.1% change in energy consumption for a 10% change in mass. Additionally, the less efficient the vehicle's powertrain, the

larger the energy consumption benefits were for mass reduction.

INTRODUCTION

The impact of vehicle mass on vehicle road load and energy consumption for three vehicle powertrain architectures was determined through coastdown testing and chassis dynamometer testing. This testing was conducted on a Ford Fusion V6 internal combustion engine (ICE) vehicle, Ford Fusion Hybrid electric vehicle (HEV), and a Nissan Leaf battery electric vehicle (BEV). Testing was conducted at multiple test weights for each vehicle. Hopefully, the results of this testing and analysis will supply future research and modeling efforts with additional, valuable results.

Background
It is widely accepted that increased vehicle mass adversely affects vehicle fuel economy. The vehicle has to consume additional energy to accelerate the heavier vehicle, as well as increased rolling drag (wheel bearing and tire); therefore, it requires more energy to propel the vehicle. Equation 1 [1] shows the drag forces acting on a vehicle while driving. Note that the rolling resistance portion of the force is directly proportional to vehicle mass.

$$F_{drag} = C_{rr}\,N + \frac{1}{2}\rho v^2 C_d A \qquad \text{Equation 1}$$

where:

F_{drag} is the drag force (N)
C_{rr} is the coefficient of rolling resistance
N is the normal force (mass of the vehicle) (N)
ρ is the density of the fluid (kg/m^3)
v is the velocity of the vehicle (m/s)
C_d is the aerodynamic drag coefficient
A is the frontal area of the vehicle. (m^2)

From several literature references of Environmental Protection Agency (EPA) fuel economy labels of vehicles produced in the past 10 years, a clear trend can be seen showing that vehicle mass directly impacts overall vehicle fuel economy for light duty vehicles. Despite the clear trend, the magnitude of this mass impact on fuel consumption varies significantly between references. The results of the previous studies show that a decrease in mass of 250 lb results in an improvement in fuel economy of 0.53 to 1.6 miles per gallon (mpg) for ICE technology. [2][3][4][5][6]

Project Description

The objectives for this study are to determine the impact of vehicle mass on vehicle road load force and fuel economy or energy consumption (mpg and Wh/mi). Additionally, the study investigates the relationship of powertrain architecture (ICE, HEV, or BEV) and vehicle mass on the impact to road load force and fuel economy or energy consumption.

This study was funded by the U.S. Department of Energy's Office of Energy Efficiency & Renewable Energy Vehicle Technologies Program to produce referenceable results for the impact of vehicle mass on road load force and vehicle energy consumption. Three teams collaborated to successfully complete this study. The Idaho National Laboratory led the study, conducted analysis on coastdown testing data, and is responsible for reporting the results. ECOtality North America procured and prepared the vehicles and conducted the coastdown testing and data collection. Argonne National Laboratory conducted the chassis dynamometer testing and energy consumption analysis.

TESTING METHODOLOGY

To accomplish the objectives, three vehicles were selected for testing. The vehicles are the Ford Fusion V6 (ICE), the Ford Fusion Hybrid (HEV), and the Nissan Leaf (BEV). The Nissan Leaf was chosen because it is the best selling BEV in North America (largest volume). The Ford Fusions were chosen because the Ford Fusion has a conventional and hybrid electric powertrain option in the same platform, which will provide the most direct comparison when investigating the impact of powertrain architecture difference between ICE and HEV. Figure 1 shows the three vehicles used for testing throughout this study. Table 1 shows the vehicle specifications.

Figure 1 – Picture of the Ford Fusion Hybrid (HEV), Nissan Leaf (BEV), and Ford Fusion V6 (ICE) tested in this study.

Table 1– Test vehicle specifications.

	Conventional	**Hybrid Electric**	**Battery Electric**
Vehicle	Fusion V6 ICE	Fusion Hybrid	Leaf BEV
EPA label (city/highway)	20/28	41/36	106/92 mpgge
Curb weight [lb]*	3,548	3,805	3,377
ETW [lb]	3,750	4,000	3,750
Engine/motor specifications**	3.0 V6 Duratec 24V PI 10.3:1 compression ratio 240 HP @ 6,550 rpm 223 HP @ 4,300 rpm	2.5 I4 Atkinson-cycle PI 12.3:1 compression ratio 156 HP @ 6,000 rpm 136 HP @ 2,250 rpm	80 KW AC synchronous electric motor 107 HP 207 lb/ft
Traction battery**	NA	NiMH 275-volt/36 kW	Lithium-ion Capacity 24 kWh
Transmission**	6 speed automatic 3.56:1 final drive	Power split	Single-speed gear reduction

* Car and driver
** Original equipment manufacturer website

Coastdown testing was conducted on each of the three vehicles to determine the road load forces at multiple test weights above and below EPA certification weight. The vehicle road load force was the overall force on the vehicle resisting forward motion, which includes aerodynamic drag and rolling drag, as described in Equation 1 [1] above. The vehicle road load force was calculated from the measured mass of the vehicle and the vehicle's decreasing change in speed while coasting.

Chassis dynamometer testing was conducted over standardized drive cycles (Urban Dynamometer Drive Schedule [UDDS], Highway Fuel Economy Test [HWFET], and US06) to determine the fuel consumption or electrical energy consumption for each vehicle at multiple test weights above and below EPA certification weight. The road load force determined from coastdown testing for each vehicle at each test weight is used to configure the chassis dynamometer. A chassis dynamometer was used in this study due to the accuracy and repeatability for measuring energy consumption, because ambient conditions were regulated to consistently tight tolerances and the driving pattern is predetermined. Additionally, the chassis dynamometer had an inherent benefit of the ability to test at various vehicle test weights without physically altering the vehicle. The vehicle test weight was part of the dynamometer's road load emulation. This allowed for a wide range of vehicle test weights to be studied quickly.

Testing posed several challenges for obtaining accurate results. Prior to commencing testing, all of the vehicles accumulated more than 4,000 miles to ensure the results from testing were not impacted by break-in effects. Road load force is likely to change while the vehicle is breaking-in due to multiple suspension and driveline components. The same three vehicles were used throughout the study to avoid vehicle-to-vehicle variation, even within the same make and model vehicle. With coastdown testing, the vehicle road load force can be affected by many factors in addition to vehicle mass. These factors include aerodynamic changes (such as vehicle ride height and rake), ambient conditions (like wind, temperature, and humidity), and even the thermal state of the vehicle's components (including driveline fluids, wheel bearing, and tire temperature) dramatically impacts the road load measurement. All of these factors, if not consistent throughout testing, would impact the coastdown testing and, thus, impact calculated road load force. Careful planning and testing were conducted to attempt to nullify the effects from the other factors during testing by ensuring consistency throughout all testing. Chassis dynamometer testing also required attention to detail because many external factors significantly impact the measured fuel consumption and electrical energy consumption during testing. These factors included ambient and vehicle temperatures, driver variations, control system energy management repeatability, and accessory utilization. As with coastdown testing, careful planning and testing execution attempted to nullify the effects from the other factors during testing by ensuring they remained consistent throughout all testing.

Coastdown Testing

Coastdown testing was conducted on a closed test track in the Phoenix area and consisted of a 2-mile straight-away. For each vehicle, at each test weight, a minimum of 14 coastdown tests were conducted to reduce sensitivity to external variables. This provided a large enough sample set to identify and remove outlier tests. The coastdown tests were conducted in pairs coasting in opposite directions on the same section of track (i.e., to the northeast and then to the southwest). This was an effort to nullify any effects from track grade variability and wind effects. Acceptable testing conditions for wind, ambient temperature, and humidity limits were strictly adhered to per the SAE J1263 standard. Additionally, to reduce testing variability, multiple procedures were utilized to reduce external impacts on the coastdown testing. Each vehicle was warmed up for 30 minutes prior to testing by driving at highway speeds (55 mph) to ensure the powertrain and driveline components and fluids were at proper operating temperature. For the various test weights, the vehicle ride height was held to ±1.0 cm at each of the vehicle's four corners by the use of a spring spacer. Without retaining the vehicle ride height, the aerodynamic drag would likely be impacted and, therefore, the road load measurement would be impacted. This would provide undesirable results because this study focused on mass impacts without change to aerodynamic drag. In a continued effort to provide quality and repeatable results, several temperatures were monitored and recorded to ensure the vehicle was functioning at steady-state operating conditions. These temperatures included transmission fluid temperature and tire side wall temperature using a non-contact temperature sensor.

The test weights chosen for coastdown testing included weights heavier and lighter than the EPA certification test weight. The EPA certification weight was curb weight plus an additional 332 lb, which included the driver and typical cargo or luggage. It was important for this study to understand the impact of both increased vehicle mass and light-weighting efforts on road load force and energy consumption. Table 2 shows the test weights used for the three vehicles for coastdown testing. The heavier test weights were achieved by adding ballast to the vehicle near the vehicle's center of mass. This was done in order to reduce the level of effort of adjustment to maintain ride height. For the test weights lighter than the EPA certification weight, the ballast for the 332 lb was removed and the interior bolt-on components (such as the spare tire, jack, seats, and other interior components) were removed. The lightest test weight was 250 lb less than the EPA certification weight. A test weight beyond this would require significant and permanent modifications to the vehicle. Modifications were deemed inappropriate and unnecessary given the spread of achievable test weights.

Table 2 – Vehicle test weights utilized for coastdown testing.

	Fusion ICE (V6)	Fusion HEV	Leaf BEV
+500 lb	4,250	4,500	4,250
+250 lb	4,000	4,250	4,000
EPA cert. weight	3,750	4,000	3,750
-100 lb	3,650	3,900	3,650
-250 lb	3,500	3,750	3,500

Dynamometer Testing

Fuel or energy consumption was measured for each vehicle at each test weight over standardized drive cycles using a chassis dynamometer. A chassis dynamometer provides a very accurate and repeatable means of measuring energy consumption. This is important for this study because the incremental change in energy consumption is small between the various test weights of the vehicle. The drive cycles used were the UDDS, HWFET, and US06. As with coastdown testing, many measures were utilized to ensure consistent results from test to test, but also for comparison to coastdown testing. To reduce testing variability prior to the on-dynamometer coastdown and vehicle loss determination, each vehicle was warmed up per dynamometer test procedures. The same temperatures as with the coastdown testing were monitored and recorded to ensure the vehicle was functioning at the same steady-state operating conditions. Monitored temperatures included transmission fluid temperature and the tire side wall temperature by a non-contact temperature sensor. For each vehicle, the same sensors and sensor positioning used during the coastdown testing were also used in the dynamometer testing. This allowed the coastdown and dynamometer testing to be cross referenced and analyzed for the same vehicle for a given test weight.

The test weights chosen for the dynamometer testing included weights heavier and lighter than the EPA certification test weight. Table 3 shows the test weights used for the chassis dynamometer testing.

Table 3 – Vehicle test weights for dynamometer testing.

	Fusion ICE (V6)	Fusion HEV	Leaf BEV
+500 lb	4,250	4,500	4,250
EPA cert. weight	3,750	4,000	3,750
-250 lb	3,500	3,750	3,500
-500 lb	3,250	3,500	3,250

Three of the test weights were identical to the test weights used during coastdown testing, but the lightest test weight was 250 lb less than the lightest coastdown test weight. This was possible because the chassis dynamometer does not require the actual vehicle weight to be modified for each test weight. The dynamometer test weight was part of the road load emulation controlled by the chassis dynamometer control system.

Therefore, the lightest test weight (i.e., -500 lb) could be readily achieved for chassis dynamometer testing. In comparison, achieving the -500-lb test weight for track testing would require significant vehicle modification.

Study Assumptions and Limitations

This study had particular assumptions and limitations that were inherent to the physical nature of the study or were constraints placed upon the study in order to retain consistency and repeatability. These limitations were as follows:

• Each vehicle powertrain remained unchanged for each test weight; therefore, the mass compounding effect was not considered in this study. If vehicle mass was reduced during the design phase of development, the sizing of the powertrain and other subsystems could be reduced for equivalent vehicle performance. This downsizing further reduced the overall vehicle mass and further reduced energy consumption.

• The results per vehicle category were based on results from a single car and inherently were not the results for all vehicles of the same type or vehicle class.

• Road load input to the dynamometer testing was based on the track test coastdown results.

• Manufacturer recommended tire pressure was maintained for all test weight cases per vehicle during all phases of testing.

TESTING RESULTS, ANALYSIS, AND DISCUSSION

Coastdown Testing

Coastdown testing was conducted for each vehicle at each test weight and consisted of a minimum of 14 coastdown tests at each condition. The results shown in Figure 2 are the average of the 14 coastdown tests at each test weight for each vehicle. Note the progression of increasing coast time for increasing test weight. Two opposing factors were in effect. With increasing mass, the vehicle inertia increased, which increased the coastdown time; however, also with increasing mass, the rolling resistance forces increased, which decreased the coastdown time. Because the overall coastdown times slightly increased, the vehicle's momentum had a larger impact on the coastdown time than the rolling resistance.

From the coastdown vehicle speed profile, the average road load force was calculated for each vehicle at each test weight as shown in Figure 3. The calculation uses the measured mass of the vehicle and the measured deceleration of the vehicle to calculate the road load force acting on the vehicle. The road load was calculated for each coastdown run. The fourteen road loads were averaged together to obtain a single average road load for each test weight for each vehicle. Figure 3 shows the averaged road load force for each test weight for each vehicle.
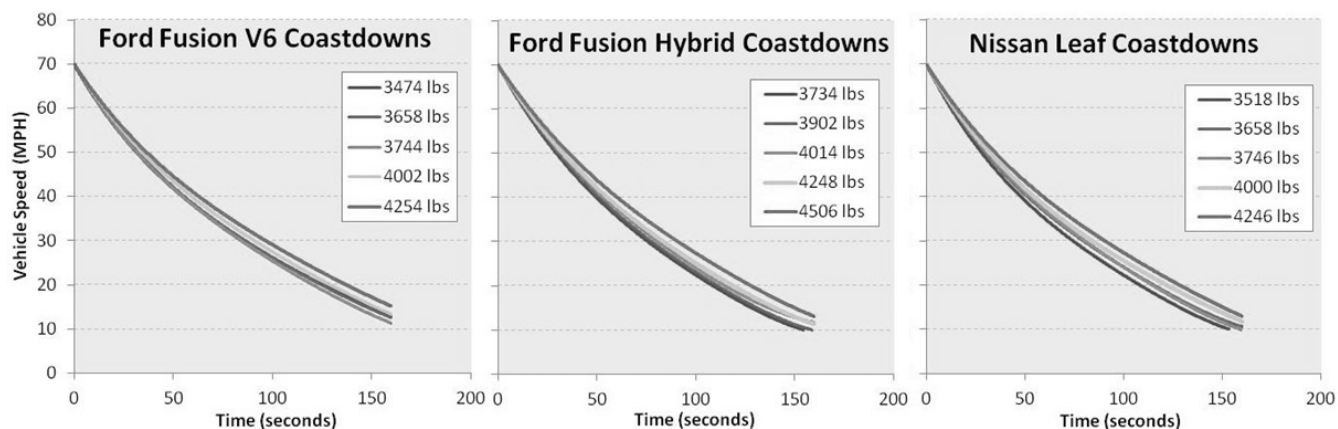
Figure 2 – Coastdown speeds for the three vehicles at each of the five test weights.
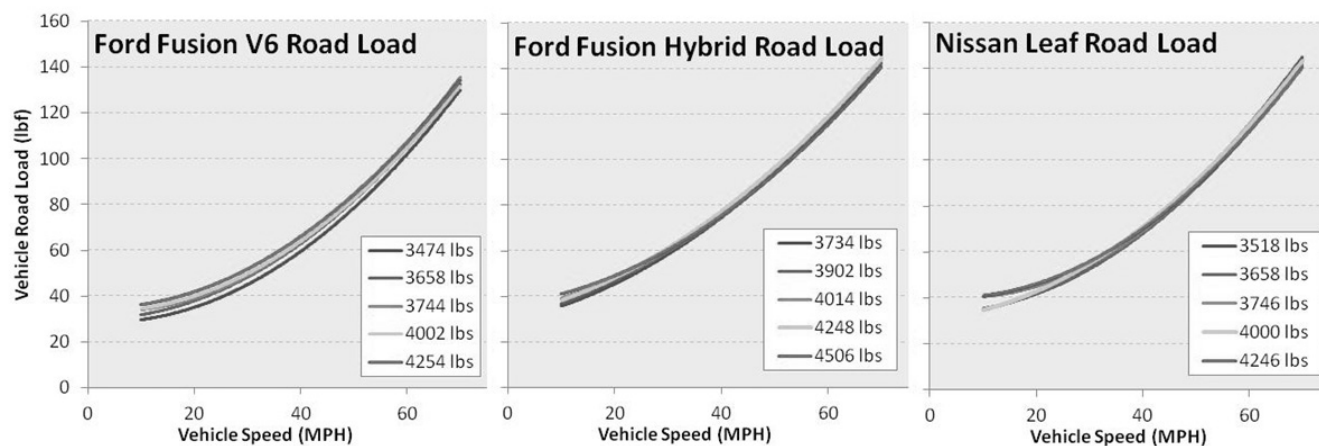
Figure 3 – Road load for the three vehicles at each of the five test weights.

A small speed-dependant trend can be seen from all three vehicles. This trend shows a convergence of road load force of the five test weights at higher vehicle speeds. This trend appears more evident from the results of the Ford Fusion Hybrid and the Nissan Leaf. Because all of the external factors were held constant as much as possible across the various test weights, another effect must be present. A possible parameter that may have had an effect was the transmission neutral state control for a vehicle without a mechanical neutral. The Ford Fusion Hybrid and the Nissan Leaf do not have a true mechanical neutral. A true mechanical neutral involves the physical disconnection of mechanical drivetrain components to disable any torque transfer from the powertrain to the vehicle's wheels. This lack of true neutral requires the powertrain control system to operate the powertrain such that no output torque is delivered. Without further testing, it cannot be conclusively determined if this possible effect was the cause of the convergence of the road load forces at higher speeds or perhaps another reason not yet identified.

Many factors impact the road load force on a vehicle. The factor with the largest impact is vehicle speed, whereas the vehicle mass has much less impact on road load force. Equation 1 shows this where the velocity term is squared and the normal force term is linear. Figure 4 shows the road load force versus vehicle speed and vehicle mass for only the Ford

Fusion Hybrid. Similar results are apparent for the other vehicles tested. The impact of vehicle mass at 10 mph is highlighted in pink to show the slight increase in road load force with increasing vehicle mass. At higher speeds, a similar increase in road load occurs; however, for visual clarity, only the road load impact at 10 mph is highlighted in pink in Figure 4.

For this study, the impact of mass on the vehicle road load, independent of other factors, was difficult to isolate due to the magnitude of the speed impact difference compared to mass impact.

From the averaged road load force calculated for each vehicle test weight shown in Figure 3, the low-speed change in road load is shown in Figure 5. For comparison of the three vehicles, the results are shown in percent change in road load force versus percent change in vehicle test weight with respect to EPA certification test weight. For all three vehicles, a slightly non-linear trend was apparent. This result is noteworthy because the classic drag force equation indicates a linear trend between mass and force from rolling resistance.
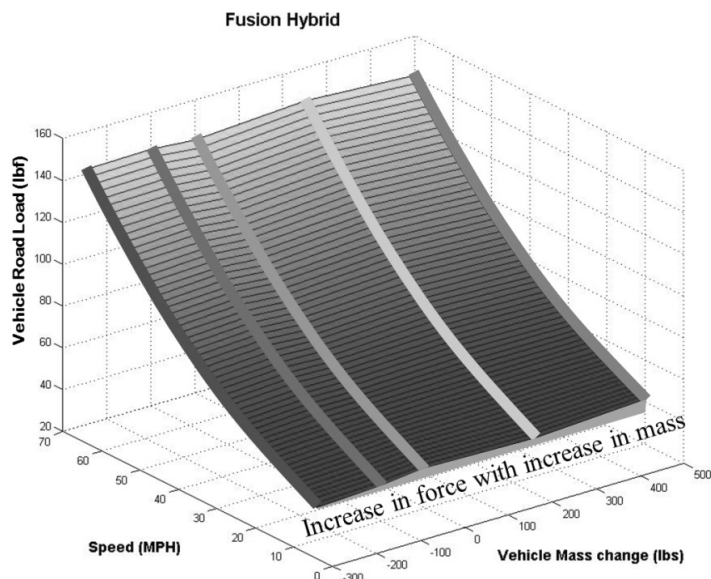
Figure 4 – Road load versus speed versus vehicle mass for the Ford Fusion Hybrid.
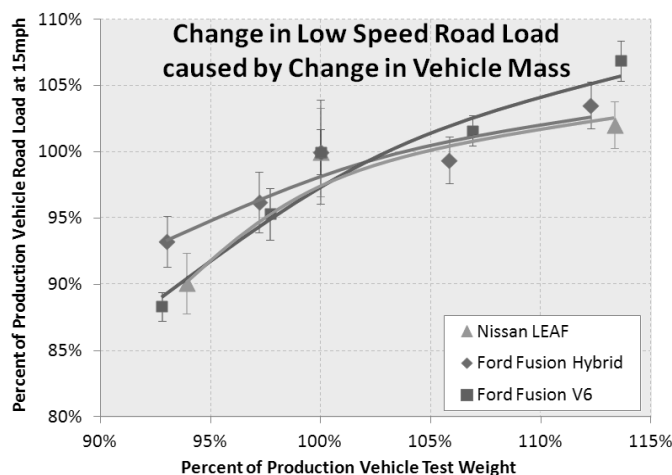
Figure 5 – Percent change in road load versus percent change in vehicle mass at 15 mph.

Dynamometer Testing

The three vehicles were tested on the chassis dynamometer at Argonne's Advanced Powertrain Research Facility. The track test weights and resulting road load curves from the track were used as an input to the chassis dynamometer. The test weight from the track was entered to the closest pound.

Test setup:
Each vehicle was tested continuously at its different test weights on the same chassis dynamometer. The target coefficients (A, B, and C) utilized for the dynamometer testing were directly derived from the coastdown testing and analysis described in the previous section. This was accomplished by curve fitting a three-term equation to each of the five vehicle road load curves for each vehicle (as shown in Figure 3). For each vehicle, a vehicle loss determination procedure was performed on the chassis dynamometer. A pair of HWFET test cycles was used as the vehicle warm up. Immediately following this warm-up, the dynamometer coastdown

correlation procedure was executed to determine the vehicle losses. The vehicle losses determination was performed only once for each vehicle because vehicle loss does not change across the various test conditions on the dynamometer. The vehicle losses and target coefficients were used to derive the dynamometer set coefficients required for testing, which dictate the actual loading of the dynamometer onto the vehicle under test.

Test plan:
One test weight category was tested per day per vehicle. Each test weight category was tested at least three times to establish a confidence interval in the fuel and energy consumption results from the chassis dynamometer testing.

The test plan for the conventional vehicle and the HEV for each test weight included the following sequence: cold-start UDDS, hot-start UDDS, HWFET pair, andUS06 pair. At the end of the day, a UDDS prep cycle was performed at the test weight category of the next day. The consistent test plan was performed to maintain consistent thermal conditions, obtain charge-sustaining results, and set a repetitive pattern for the test staff to minimize mistakes.

The test plan of the electric vehicle was based on the SAE J1635 multi-cycle test shortcut method. The electric vehicle is fully charged at the beginning of testing. The vehicle is tested in the following sequence: cold start UDDS, single HWFET, UDDS, single US06, single US06, UDDS, highway, steady-state speeds, and maximum acceleration test. The energy consumption for the different test cycles is then calculated using the 'usable battery energy' and the weight cycle energy consumption results.

The test cycles used are U.S. certification cycles that represent different driving patterns. The UDDS represents city-type driving, the HWFET represents highway-type driving, and the US06 represents aggressive and higher speed driving (as shown in Figure 6).

The driver for each vehicle during the dynamometer testing was the same for each vehicle to minimize variations induced by different drivers.

*Fuel and energy consumption measurements:*
The fuel was measured using a direct fuel flow meter in line with the vehicle fuel pump and the fuel rail at the engine. A Hioki power analyzer was used to measure the DC power and net DC energy in and out of the high-voltage battery pack for the electric vehicle and the HEV. The power analyzer measurements on the HEV were used to verify that the tests were in charge-sustaining mode.

Raw chassis dynamometer test results:
Figures 7, 8, and 9 present the average fuel consumption results as a function of vehicle test weight. Each average fuel consumption test result was framed by a 95% confidence interval.
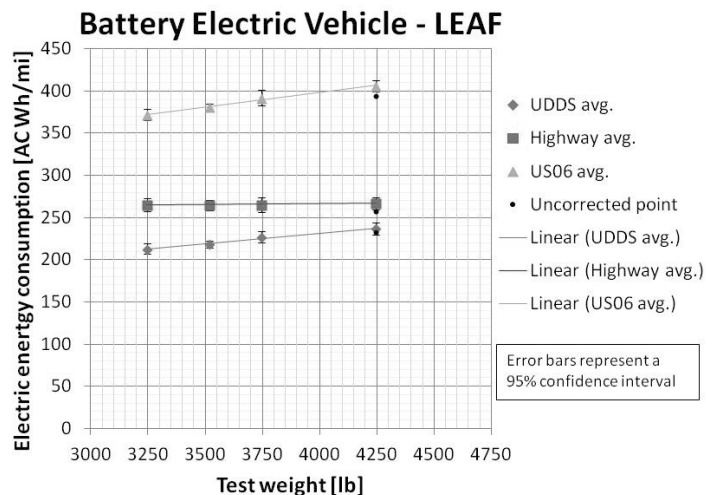
INL/CON-12-27455
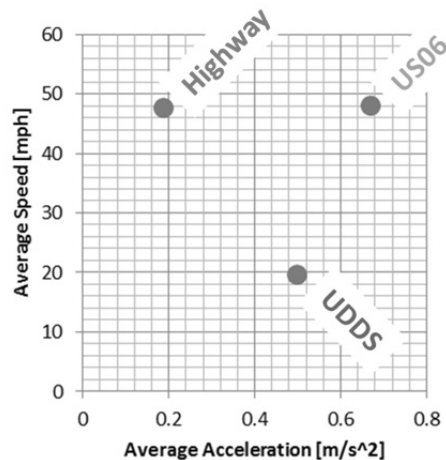
Figure 6 – *Average speed and acceleration distribution of the UDDS, highway, and US06 cycles.*
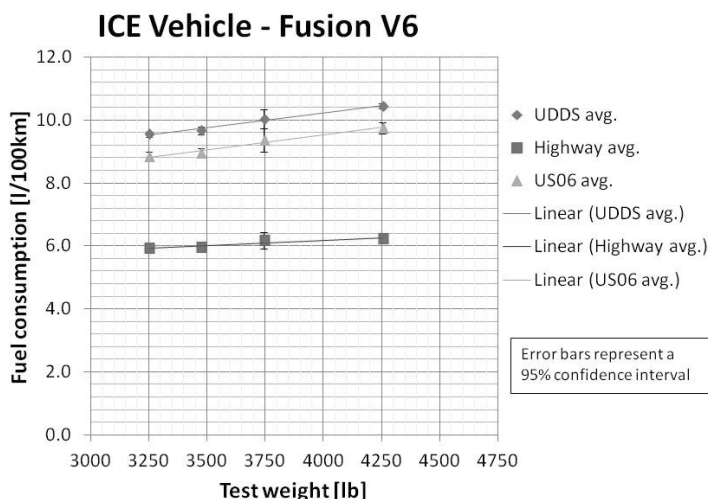
Figure 7 – *Fuel consumption of the Ford Fusion V6 at numerous test weights.*
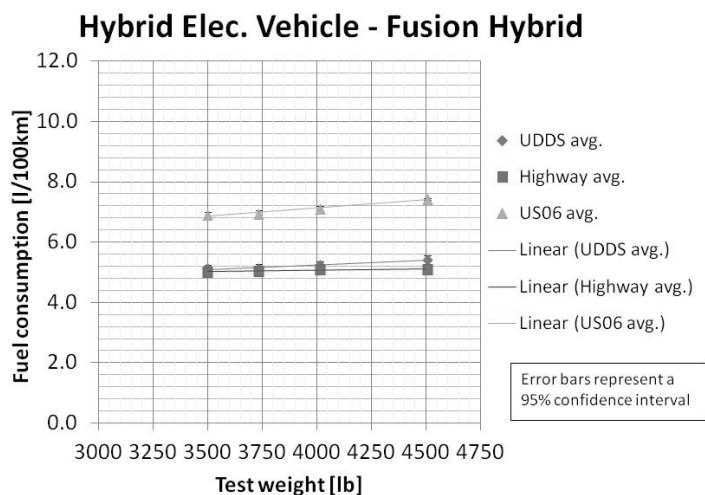
Figure 8 – *Fuel consumption of the Ford Fusion Hybrid at numerous test weights.*

Figure 9 – *Fuel consumption of the Nissan Leaf at numerous test weights.*

The data shows that for all vehicles, fuel consumption increased noticeably on the UDDS and US06 test cycles, which contained higher average accelerations as shown in Figure 6. Fuel consumption on the HWFET seemed relatively unaffected by the weight change compared to the other drive cycles.

Energy consumption change in terms of mass change:
To compare the results from the three vehicles, percent change in energy consumption over percent change in vehicle mass was chosen as the metric, because fuel consumption (l/100km) and electrical energy consumption (Wh/mi) were not readily comparable. Additionally, the absolute energy consumption savings is represented in liter of gasoline equivalent, which is calculated for the electric vehicle based on the AC energy consumption and the energy content of gasoline.
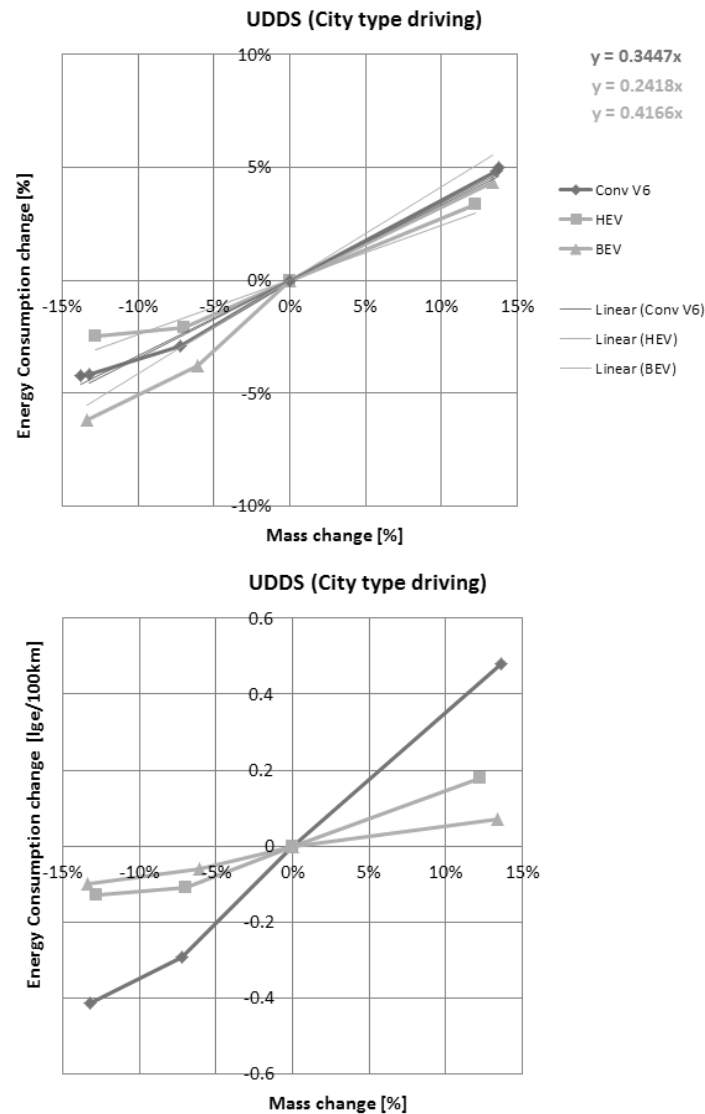
Figures 10, 11, and 12 show the energy consumption rate of change and the absolute fuel savings as a function of rate of vehicle mass change.

The largest proportional energy change occurred in the city and during aggressive-type driving. In these cycles, where the vehicle accelerated often, the vehicle mass had a direct impact on the inertia energy required to move the vehicle forward. Because the inertial power required to move a vehicle was calculated by multiplying acceleration by mass, any mass change to a vehicle has a direct and proportional impact on the energy required to accelerate the vehicle. This effect was displayed in the data in the cycles dominated by acceleration. The highway cycle energy required to move the vehicle was dominated by the road load because the vehicle was cruising at relatively steady speeds.

In the energy consumption rate change graphs (i.e., the top graphs), all of the vehicles seemed to be clustered relatively closely. Perhaps the electric vehicle might experience the largest benefit in range increase on a full battery per mass saved. In the absolute energy or fuel savings graphs (i.e., the

bottom graphs), light-weight conventional vehicles provide the largest fuel savings per mass saved, because the conventional vehicles have the lowest vehicle efficiency.

Linearizing the energy consumption change with respect to the vehicle mass change eliminated some of the details that are shown in Figures 10 through 12. Table 4 shows the results in a ratio of the percent change in energy consumption to percent change in mass.

US06 (Agressive type driving)

$y = 0.3824x$
$y = 0.2987x$
$y = 0.3388x$

UDDS (City type driving)

$y = 0.3447x$
$y = 0.2418x$
$y = 0.4166x$

UDDS (City type driving)

Figure 10 – Percent change in energy consumption vs. percent change in vehicle mass on the UDDS drive cycle.

US06 (Agressive type driving)
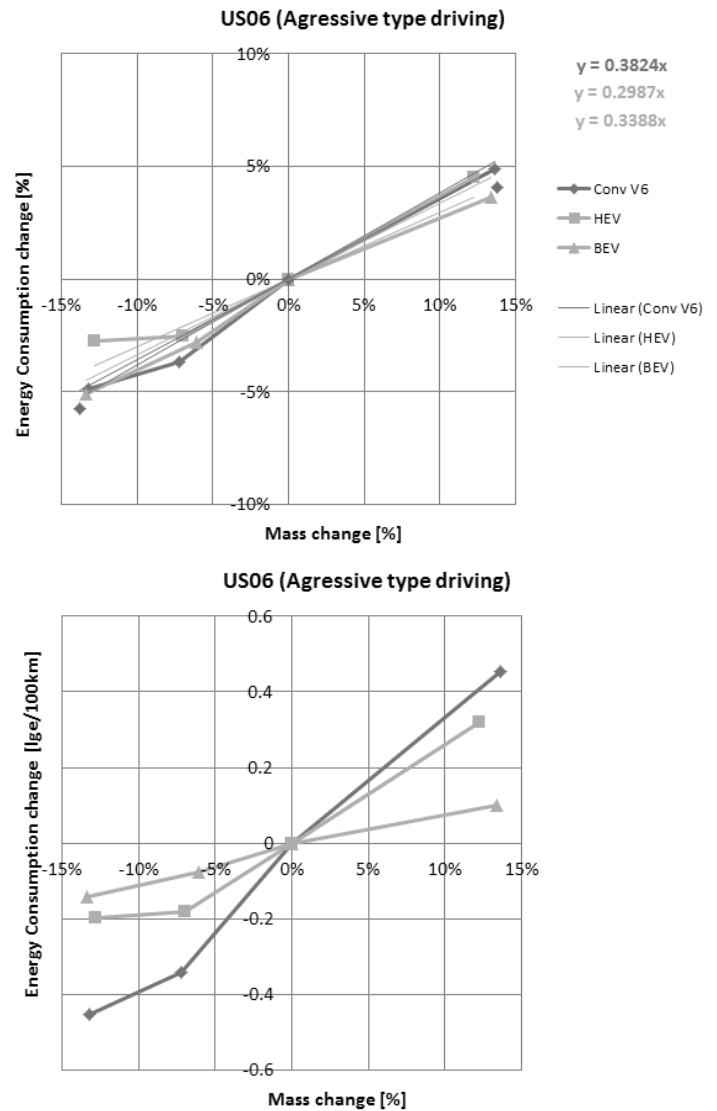
Figure 11 – Percent change in energy consumption vs. percent change in vehicle mass on the US06 drive cycle.

The previously referenced studies claimed that a decrease in vehicle mass of 250 lb resulted in an improvement in fuel economy of 0.53 to 1.6 Mpg for conventional vehicle technology. [2][3][4][5][6] This was equivalent to a ratio of 0.37 to 1.2% energy consumption for percent mass change. These references varied in results because some included mass compounding (i.e., decreased powertrain and component sizing with chassis mass reduction), while other references did not include mass compounding. The lower range of ratios did not include mass compounding. Because the three-vehicle comparison detailed in this paper did not include mass compounding (i.e. the powertrain was identical for each test weight), it was appropriate that the results of this study (as shown in Table 4) for the conventional ICE vehicle correlate to the lower range of the reference results.

HWY (Highway type driving)

HWY (Highway type driving)

Figure 12 – Percent change in energy consumption vs. percent change in vehicle mass on the highway drive cycle.

Table 4 – Results of percent change in energy per percent change in vehicle mass.

Percent Energy Consumption/Percent Mass Change Ratio			
Driving type	**Highway**	**Aggressive**	**City**
Fusion V6	0.21	0.38	0.34
Fusion Hybrid	0.08	0.30	0.24
Nissan Leaf	0.03	0.34	0.42

SUMMARY

This study investigated and quantified the impact of vehicle mass on the road load and energy consumption of three vehicles of varying powertrain architecture. The vehicles tested were the Ford Fusion V6 (ICE), the Ford Fusion Hybrid (HEV), and the Nissan Leaf (BEV). Each vehicle was tested at multiple test weights lighter and heavier than the EPA certification test weight. This study investigated the impact of increased vehicle mass and vehicle light-weighting on vehicle road load force and energy consumption.
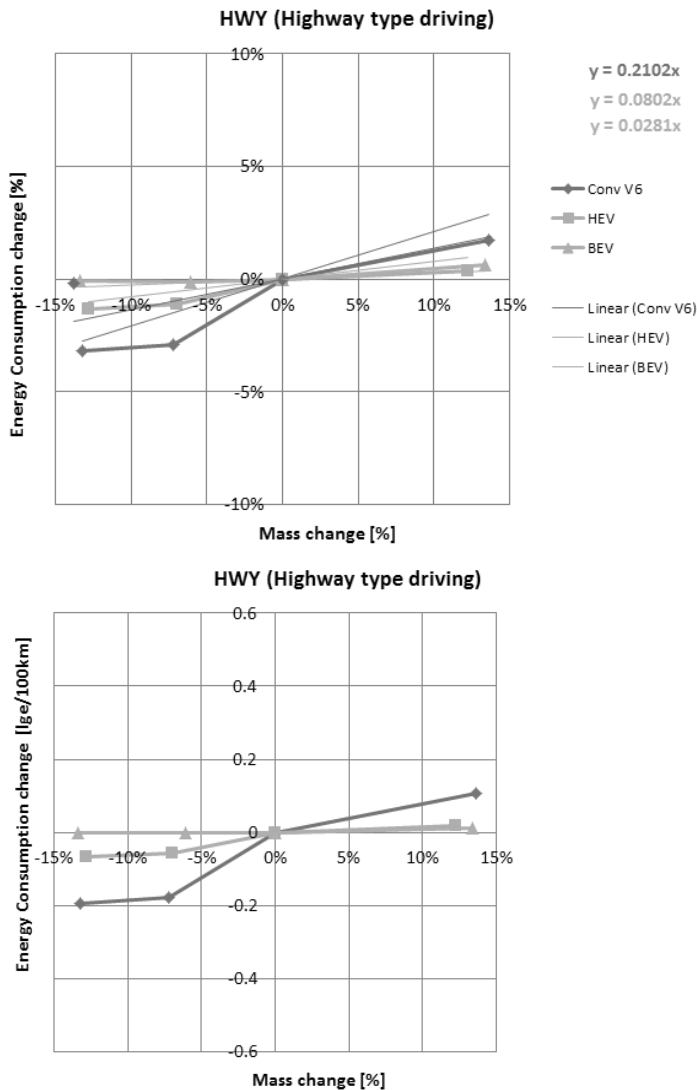
Coastdown testing and analysis was conducted to measure the impact of weight mass on vehicle road load. For the three vehicles, a slightly non-linear trend in decreasing road load was measured versus decreasing vehicle mass. The non-linear aspect of the trend showed increasing vehicle mass impacted road load less than decreasing vehicle mass of the same amount. Analysis of coastdown testing provided road load data to enable accurate chassis dynamometer testing.

The chassis dynamometer testing showed that in city-type driving and aggressive-type driving, a 10% mass reduction can result in a 3 to 4% energy consumption reduction for the conventional ICE engine, HEV, and electric vehicles. The energy consumption benefit appeared to be linked to the reduction in inertia energy required to accelerate the vehicle. Vehicle mass change did not appear to have a large impact on energy consumption in highway-type driving.

The largest absolute fuel savings can be achieved by mass reduction in a conventional vehicle because powertrain efficiency was the lowest of the three vehicles tested in this study; therefore, it had the largest overall energy consumption impact.

Vehicle mass significantly impacted energy consumption during stop and go driving (such as city driving). Conversely, highway driving proved to have little impact from vehicle mass on energy consumption.

The results of this study were specific for the three vehicles tested (i.e., the 2012 Ford Fusion V6 ICE, 2012 Ford Fusion Hybrid HEV, and 2011 Nissan Leaf BEV). Though some general conclusions can be drawn from these results, they do not dictate the results for other makes and models of ICE vehicles, HEVs, and BEVs.

INL/CON-12-27455

REFERENCES

1. http://www.engr.colostate.edu/~allan/fluids/page8/page8.html, 2005.
2. Cheah, L., "Cars on a Diet: Material and Energy Impacts of Passenger Vehicle Weight Reduction in the U.S.," Massachusetts Institute of Technology, http://web.mit.edu/sloan-auto-lab/research/beforeh2/files/LCheah_PhD_thesis_2010.pdf, 2010.
3. Cheah, L., et al., "Factor of Two: Halving the Fuel Consumption of New U.S. Automobiles by 2035," Massachusetts Institute of Technology, http://web.mit.edu/sloan-auto-lab/research/beforeh2/files/cheah_factorTwo.pdf, 2007.
4. Pagerit, S., Sharer, P., and Rousseau, A., "Fuel Economy Sensitivity to Vehicle Mass for Advanced Vehicle Powertrains," SAE Technical Paper 2006-01-0665, 2006, doi:10.4271/2006-01-0665.
5. http://www.engin.umich.edu/labs/EAST/me589/gallery/materials_auto_f05/weight_mpg.html, University of Michigan, 2005.
6. http://www.magnesium.com/w3/forum/read.php?thread=2772.
7. An, F. and Santini, D., "Mass Impacts on Fuel Economies of Conventional vs. Hybrid Electric Vehicles," SAE Technical Paper 2004-01-0572, 2004, doi:10.4271/2004-01-0572.
8. Wohlecker, R., Johannaber, M., and Espig, M., "Determination of Weight Elasticity of Fuel Economy for ICE, Hybrid and Fuel Cell Vehicles," SAE Technical Paper 2007-01-0343, 2007, doi:10.4271/2007-01-0343.
9. LaPointe, C., "Factors Affecting Vehicle Fuel Economy," SAE Technical Paper 730791, 1973, doi:10.4271/730791.
10. Youngren, H., "Engineering for Better Fuel Economy," SAE Technical Paper 410132, 1941, doi:10.4271/410132.
11. http://www.wired.com/wiredscience/2012/08/fuel-economy-vs-mass/, Sothern Louisiana University, 2012.
12. Hochgraf, C., "2010 North American Light Duty Vehicle Assessment: The Ten Most Efficient Powertrains, The Ten Lowest Energy Consumption Chassis," SAE Technical Paper 2011-01-0889, 2011, doi:10.4271/2011-01-0889.
13. http://www.sciencedirect.com/science/article/pii/S136192090900011X.
14. SAE Automotive Engineering Magazine, "Heavy on Lightweighting," October 2012, page 50, http://magazine.sae.org/12aeid1002.
15. SAE Automotive Engineering Magazine, "Lighten Up!" March 2009, page 16, http://magazine.sae.org/AUTOMAR09.

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