

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.

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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.



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

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.

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

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/m³)

v is the velocity of the vehicle (m/s)

C_d is the aerodynamic drag coefficient

A is the frontal area of the vehicle. (m²)

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.

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

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

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-