

Fuel Economy and Emissions Effects of Low Tire Pressure, Open Windows, Roof Top and Hitch-Mounted Cargo, and Trailer

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ABSTRACT

To quantify the fuel economy (FE) effect of some common vehicle accessories or alterations, a compact passenger sedan and a sport utility vehicle (SUV) were subjected to SAE J2263 coastdown procedures. Coastdowns were conducted with low tire pressure, all windows open, with a roof top or hitch-mounted cargo carrier, and with the SUV pulling an enclosed cargo trailer. From these coastdowns, vehicle dynamometer coefficients were developed which enabled the execution of vehicle dynamometer experiments to determine the effect of these changes on vehicle FE and emissions over standard drive cycles and at steady highway speeds. In addition, two minivans were subjected to coastdowns to examine the similarity in derived coefficients for two duplicate vehicles of the same model.

The FE penalty associated with the rooftop cargo box mounted on the compact sedan was as high as 25-27% at higher speeds, where the aerodynamic drag is most pronounced. For both vehicles, use of a hitch mounted cargo tray carrying a similar load resulted in very small FE penalties, unlike the rooftop cargo box. The results for the SUV pulling a 3500 pound enclosed cargo trailer were rather dramatic, resulting in FE penalties ranging from 30%, for the city cycle, to 50% at 80 mph, at which point significant CO generation indicated protective enrichment due to high load. Low tire pressure cases resulted in negligible to 10% FE penalty depending on the specific case and test point. Driving with all four windows open decreased FE by 4-8.5% for the compact sedan, and 1-4% for the SUV.

CITATION: Thomas, J., Huff, S., and West, B., "Fuel Economy and Emissions Effects of Low Tire Pressure, Open Windows, Roof Top and Hitch-Mounted Cargo, and Trailer," *SAE Int. J. Passeng. Cars - Mech. Syst.* 7(2):2014, doi:10.4271/2014-01-1614.

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 website (www.fueleconomy.gov) that helps fulfill their responsibility under the Energy Policy Act of 1992 to provide accurate FE information to consumers. The site provides EPA FE ratings for passenger cars and light trucks from 1984 to the present, information on alternative fuels, driving and vehicle maintenance tips, and other relevant information related to vehicle energy use. Additionally, the site provides consumer information and advice pertaining to methods for improving real world FE. Under the auspices of this program, the Oak Ridge National Laboratory (ORNL) Fuels, Engines, and Emissions Research Center (FEERC) conducts studies to validate and improve this information. This paper documents a study aimed specifically at the effects of common vehicle in-use alterations or modifications such as trailer towing, use of rooftop cargo boxes versus hitch-mounted cargo trays, low tire pressure, and open windows. Previous studies have detailed the impact of intake air filters, highway cruise speed, and air conditioning on fuel economy of light-duty vehicles [1, 2, 3, 4].

A vehicle's published EPA FE rating is determined by driving the vehicle over prescribed cycles on a chassis dynamometer. City FE is measured using the Federal Test Procedure (FTP). Highway FE is measured using the Highway Fuel Economy Test (HFET). Additional tests such as the US06, SC03, and cold CO test are conducted as part of certification to confirm emissions compliance during aggressive driving, at very hot conditions with air conditioning, and at very cold temperatures, respectively. Typically FE results from these tests are not reported, but EPA uses results from these cycles to adjust the FTP and HFET results [5], and these adjusted FE rates are reported on the vehicle manufacturer's window sticker, in the Fuel Economy Guide [6], and on the [fueleconomy.gov](http://www.fueleconomy.gov) website. Vehicle conditions for these tests are generally at curb weight plus 300 pounds, with proper tire pressure, windows up, and air conditioner off (except for the SC03)[7]. Vehicles are subjected to the SAE Standard J2263 coastdown procedure to develop target vehicle dynamometer coefficients to enable the laboratory vehicle dynamometer to mimic the on-road conditions [8]. Changes to the vehicle rolling resistance or aerodynamic drag can result from changes in tire design, wear

or tire pressure, opening of windows, changing the weight or weight distribution, or the addition of accessories such as roof racks, cargo boxes, or trailers.

A major purpose of the fueleconomy.gov website is to provide accurate and useful information regarding the FE effects of how consumers use and drive their vehicles. However, finding relevant published test data is often difficult, with publically available data being sparse. The motivation for this study is to generate and publish quantitative results to provide validity to the advice given on the website. When performing such a study, there are inherent limitations, with the wide range of vehicle body styles, powertrain combinations, and typical modifications being very large and complex. This particular study is limited to three vehicles and six vehicle modifications.

RELATED STUDIES

A search for related work found only a few examples of experimental efforts to determine FE changes with light-duty vehicle alterations similar to or complementary to those in this paper. These studies are discussed below. Several studies of roof racks examined design and/or wind noise and forces, but did not report effect on fuel economy [9, 10, 11, 12, 13].

A 1998 study by the Swedish Road and Transport Research Institute was the most relevant work found, with similarities and complements to the current study [14]. This same study examined earlier work (before 1998) and reported limited documented efforts, with related studies mainly focused on emissions rather than FE. Steady speed on-road tests were performed at 43.5, 49.7 and 55.9 mph (70, 80 and 90 kph). This on-road study with a 1992 Volvo 940 (midsize) sedan examined the vehicle states listed below, along with the measured fuel consumption (FC) changes.

1. Standard case, 1408 kg vehicle, 2.15 m² frontal area,
2. Studded tires: no effect on FC,
3. Added roof rack: ~2% FC increase,
4. Roof rack with a ski box: ~ 10% increase in FC,
5. Pulling an open trailer, 4.3 m long, 2.2 m wide weighing 310 kg: 32-43% FC increase,
6. Trailer with a large cover having 2.36 m² exposed frontal area: 37-45% FC increase,
7. Open trailer with an additional 564 kg load: 59-75% FC increase,
8. Covered trailer with a 564 kg load: 70-83% FC increase,

In cases 5-8, the lower percent increase given is for 43.5 mph and the largest at 55.9 mph, (49.7 mph results were always between those values). Traveling at 55.9 mph compared to 43.5 mph increased FC by 13-14% for the base, studded tires and the roof rack cases. Fuel consumption increased to 17% for the ski box and 20-25% for the various trailer cases. Emissions of NO_x were examined as well, but no correlation to test condition was found.

Police vehicles (1980s large sedans) with roof-mounted light bars have been studied revealing significant measured FE effects [15, 16]. One study [15] was based on controlled experiments comparing on-road steady speed cruising at 55 mph for three 1985 model year vehicles with six different light bar designs and also for two of the vehicles with no light bar. Fuel economy was lowered by 6.6 to 11.3% for the various tested light bars compared to the absence of a light bar. This FE range revealed the differing aerodynamic performance of the installed devices (light bar weight was 19-34 pounds and presumed to be a minor factor). A study comparing in-use patrol car FE for vehicles with and without light bars found a 7% FE improvement for the vehicles without the roof-mounted lights [16].

Two recent studies have examined the FE change with rolling resistance of tires [17, 18]. Multiple tires with significantly different rolling resistance characteristics were examined between the two papers. Using coastdown testing followed by dynamometer tests on the NEDC cycle, FE differences of up to 6% were found due to the tires with rolling resistance coefficients of 0.008 to 0.0116 [17] (units: lb/lb). Steady speed test track driving at 50-56 mph showed FE differences of up to 7% for differing tires and subsequent simulations of the NEDC cycle again gave FE differences of up to 6% [18]. The effect of tire pressure on rolling resistance was not reported.

A 2001 report estimated that fuel economy decreases 0.3% for each psi below the recommended tire pressure [19]. In 2006 the Transportation Research Board issued a special report reviewing the influence of light-duty vehicle tires on FE [20]. Findings include that tire rolling resistance is typically in the range of 0.007 to 0.014 for light-duty application, and that a 10% decrease in rolling resistance can yield 1-2% FE improvement [20]. A 2008 presentation further reports that for an 8 psi or 25% decrease in tire pressure, test results show linear increases in rolling resistance from 13.7% to 19%, depending on the tire [21]. This range of rolling resistance increase and the 1-2% FE decrease per 10% increase in rolling resistance translates to a range of FE decrease of 0.17% to 0.48% per psi, similar to the 0.3% estimates in references 19 and 22.

EXPERIMENTAL SETUP

Test Vehicles

Three vehicle types were subjected to a range of J2263 coastdowns, including a 2009 Ford Explorer, a 2009 Toyota Corolla, and a pair of 2009 Honda Odyssey Minivans. Vehicles were all in good working order and wheel alignments were performed, along with other necessary maintenance, before being subjected to coastdowns on the track at Transportation Research Center (TRC) in East Liberty, Ohio.

Two vehicles were subjected to vehicle dynamometer experiments following the coastdowns. One of these was a 2009 Ford Explorer equipped with a 4.0 liter V6 engine and a

5-speed automatic transmission. This vehicle had an Equivalent Test Weight (ETW) of 5000 pounds, a frontal area of 27.3 square feet, and was outfitted with Goodyear Fortera HL 235/70-16 tires. The second vehicle was a 2009 Toyota Corolla with a 1.8 liter I4 engine and a 4 speed automatic transmission. This vehicle had an ETW of 3250 pounds, a frontal area of 21.4 square feet, and was outfitted with Goodyear Eagle LS 195/65-15 tires. The Explorer was equipped with a factory cruise control system, and a Toyota OEM cruise control kit was installed on the Corolla for the purpose of these experiments. Cruise control was used to maintain the desired speed during each of the steady state speed experiments in the laboratory. The Honda Odysseys were subjected to coastdowns to examine the similarity in derived coefficients for two duplicate vehicles of the same model. The Odysseys were equipped with Michelin Energy LX4 235/65-16 tires.

The fuel used for all dynamometer experiments was Halterman EEE Lube Spec Certification Gasoline. This fuel came in multiple batches and the fuel properties from each batch are listed in the Table in the [Appendix](#).

Determination of Dynamometer Coefficients

The forces exerted on a moving vehicle can be broken into three components, including forces due to the vehicle's inertia, gravitational forces due to traversing up or down a grade, and the Road Load Force (RLF). The RLF accounts for the vehicle's mechanical drag, i.e., rolling resistance, and aerodynamic drag. This force must be derived such that it can be duplicated by the dynamometer. The SAE procedures prescribed for deriving the RLF function is broken into two segments (the second of which will be described later). The first segment consists of coasting the vehicle down from 78 mph to 9 mph on a straight track. From the resulting speed vs. time trace, the RLF can be calculated as a function of vehicle speed.

Vehicle coastdowns were conducted by TRC per the SAE Standard J2263 procedure [8]. This procedure was updated in 1996 to incorporate advanced test equipment and data analysis, as well as making use of the capabilities of motoring dynamometers to reproduce the RLF accurately across a greater speed range using a three term second-order polynomial. Additionally, using real time anemometry mounted on a two meter boom in front of the vehicle, wind conditions can be measured and compensated for directly, allowing for reduced stringency in the required ambient conditions. The test can be conducted in the temperature range of 41 to 95°F, with an average wind speed of up to 21.7 mph (with gusts up to 31.3 mph), cross winds not exceeding 9.3 mph, and in the absence of fog or precipitation. The track must be dry, clean, straight, smooth, be hard surfaced, not excessively crowned, and ideally have no more than 0.5% grade (although corrections can be made for higher grades). A Toyota Corolla with a rooftop cargo box and front-mounted boom is shown in [Figure 1](#).



Figure 1. Toyota Corolla equipped for coast down test with a rooftop cargo box and boom.

Using the SAE J2263 Standard, an equation that represents the RLF as a function of vehicle speed can be derived. This RLF equation includes the rolling resistance and aerodynamic drag, and is given in the following form:

$$RLF = A + BV + CV^2 \quad (1)$$

In which

RLF	Road Load Force (lbf)
A	Constant term (lbf)
B	Linear term (lbf/mph)
C	Quadratic term (lbf/mph ²)
V	Vehicle speed (mph)

Dynamometer Coastdown Method

After completing the J2263 procedure, the J2264 procedure is used to develop the "Set Coefficients" on the motoring dynamometer to reproduce the RLF from the track coastdown. On the dynamometer, following a warm up procedure, the vehicle is subjected to a number of coastdowns with the transmission in neutral. These coastdowns are repeated until the system converges on a coastdown solution producing the Set Coefficients for the RLF equation that mimics the test track coastdown results. The difference between the Target Coefficients and the Set Coefficients represents the losses due to the internal dynamometer friction, differences in rolling resistance due to tire/roller contact, etc. In this way, the vehicle RLF is duplicated in the laboratory by the motoring dynamometer.

Test Vehicle Configurations

Coastdowns were conducted, per the SAE Standard J2263 procedure described above, on a sedan and SUV with various vehicle modifications which either affected the rolling resistance, aerodynamic drag, or both, as well as on two matching vans. For each vehicle condition tested, a set of Target Coefficients were determined, which represent the actual RLF experienced by the vehicle on the track. [Table 1](#)

shows the configurations tested for each vehicle, along with the Road Load Target Coefficients, and the calculated road load horsepower at 50 mph.

Table 1. Target Road Load Coefficients for each vehicle configuration tested.

2009 Toyota Corolla	Target Coefficients			hp at 50 mph
	A (lb)	B (lb/mph)	C (lb/mph ²)	
Baseline (3250 lbm)	25.07	0.2824	0.01890	11.5
Open Windows	26.26	0.2618	0.02130	12.4
75% tire pressure	31.41	0.0927	0.02120	11.9
50% tire pressure	37.70	0.2705	0.01870	13.1
Cargo Box (+120 lbm)	27.65	0.2157	0.03170	15.7
Cargo Tray (+120 lbm)	36.61	-0.1770	0.02390	11.7

2009 Ford Explorer	Target Coefficients			hp at 50 mph
	A (lb)	B (lb/mph)	C (lb/mph ²)	
Baseline (5000 lbm)	39.97	0.3672	0.03500	19.4
Open Windows	40.21	0.3673	0.03790	20.4
75% tire pressure	38.75	0.4635	0.03480	19.9
Trailer (+3500 lbm)	81.88	0.5925	0.06590	36.8
Cargo Box (+100 lbm)	39.31	0.2985	0.04450	22.1
Cargo Tray (+100 lbm)	37.17	0.6087	0.03200	19.7

Honda Odyssey (VIN 871)	Target Coefficients			hp at 50 mph
	A (lb)	B (lb/mph)	C (lb/mph ²)	
Baseline	45.105	0.19	0.031	17.5

Honda Odyssey (VIN 876)	Target Coefficients			hp at 50 mph
	A (lb)	B (lb/mph)	C (lb/mph ²)	
baseline	46.27	0.11	0.032	17.6

Open Windows

This case simply examines the increased aerodynamic drag caused by driving with all four side windows open.

Low Tire Pressure

The effect of tire pressure was examined by conducting coastdown tests with 75% of the manufacturer-recommended (gauge) tire pressure for both vehicles and at 50% of the recommended pressure for the Corolla. More specifically, the

Corolla coastdowns included all four tires at 30.0 psia for the Standard case and 22.5 and 15.0 psig for the low pressure cases. The sidewall deflection is apparent for the 50% pressure case, shown in [Figure 2](#). For the Explorer, 35.0 psig was used for the Standard case and 26.3 psig for the 75% pressure case.



Figure 2. Toyota Corolla tire with 30psi (left) and 15psi (right).

Cargo Box

The cargo box was a Sears X-Cargo (see [Figure 1](#)) which is irregularly shaped but has overall dimensions of 19, 40 and 50 inches and added about 760 in² frontal area when installed with a roof rack on the Corolla. Slightly less frontal area was added when installed on the Explorer due to the lower profile factory roof rack. The frontal area of the Corolla was increased by about 25%, and the Explorer frontal area increased about 19%. Ballast weights were added to the cargo box to make a total weight of ~100 pounds for the Explorer. The Corolla required the use of a removable roof rack, making the total added weight ~120 pounds. The coastdown test weights were checked by actually weighing the vehicles with the driver.

Cargo Tray

The cargo tray was 48 by 20 inches and attached to the trailer hitch as seen in [Figure 3](#). It was expected that only minor changes in aerodynamic drag would result from the cargo tray because no frontal area is added for this case. As with the cargo box, ballast weights were added to the cargo tray to make a total added test weight of approximately 100 pounds for the Explorer and 120 pounds for the Corolla so the results could be directly compared with the Cargo Box case.



Figure 3. Hitch mounted cargo tray mounted on Corolla.