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Fuel consumption impacts of auto roof racks

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HIGHLIGHTS

- First estimate of national energy impacts of auto roof racks—about 1‰.
- A bottom-up approach reveals details of the fuel consumption penalty caused by racks.
- Two novel data collection techniques, on-line forums and crowd-sourcing, improve estimate.
- Technical and behavioral policies could significantly cut fuel penalties from roof racks.

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ABSTRACT

The after-market roof rack is one of the most common components attached to a vehicle for carrying over-sized items, such as bicycles and skis. It is important to understand these racks' fuel consumption impacts on both individual vehicles and the national fleet because they are widely used. We estimate the national fuel consumption impacts of roof racks using a bottom-up approach. Our model incorporates real-world data and vehicle stock information to enable assessing fuel consumption impacts for several categories of vehicles, rack configurations, and usage conditions. In addition, the model draws on two new data-gathering techniques, on-line forums and crowd-sourcing. The results show that nationwide, roof racks are responsible for 0.8‰ of light duty vehicle fuel consumption in 2015, corresponding to 100 million gallons of gasoline per year. Sensitivity analyses show that results are most sensitive to the fraction of vehicles with installed roof racks but carrying no equipment. The aerodynamic efficiency of typical roof racks can be greatly improved and reduce individual vehicle fuel consumption; however, government policies to minimize extensive driving with empty racks—if successful—could save more fuel nationally.

1. Introduction

Passenger cars and passenger trucks are major petroleum consumers and contributors of greenhouse gas (GHG) and criteria pollutants emissions in many countries around the world (Oak Ridge National Laboratory, 2014; Environmental Protection Agency, 2013; Wang et al., 2009; International Energy Agency, 2009; Chen and Borken-Kleefeld, 2014). Any strategies seeking to reduce fuel consumption (FC) and emissions of the light duty vehicle (LDV)[1] fleet must involve technologies and policies addressing these vehicles (Barter, et al., 2012; Kyle and Kim, 2011; Leighty, et al., 2012; Westbrook, et al., 2014; Wu and Aliprantis, 2013; Borken-Kleefeld and Chen, 2015). In the United States (U.S.), the federal and state governments have implemented regulations to reduce LDV fuel consumption and emissions (Al-Alawi and Bradley, 2014; Kirby, 2015; Goldberg, 1998; Morrison and Chen, 2011; Chen and Fan, 2013; Chen and Fan, 2014). Because of these regulations, the average fuel efficiency of the new fleet of passenger cars and passenger trucks has increased from 28.7 and 21.3 mile per gallon (MPG) in 2000 to 35.5 and 25.3 MPG in 2013, respectively (Bureau of Transportation Statistics, 2015). Similar trends in new vehicle fuel efficiency are observed in the European Union and other countries (Global Fuel Economy Initiative, 2012). The official fuel consumption information for a specific vehicle model is typically determined by driving the vehicle according to predetermined cycles, such as the Federal Test Procedure, Highway Fuel Economy Test, US06, SC03, etc., on a chassis dynamometer

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[1] Light Duty Vehicle means a light duty truck or light duty vehicle, as such terms are defined under section 216(7) of the Clean Air Act (42 U.S.C. 7550(7)), having a gross vehicle weight rating of 8500 pounds or less, before any after-market conversion to alternative fuel operation.

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(US Environmental Protection Agency, 2006). Therefore, the measurements do not reflect after-market accessories (towing trailer, roof rack, etc.) or alternative components (low rolling resistance tires, etc.), which could result in unrepresentative fuel consumption information in real-world usage conditions. These omissions will also result in inaccurate estimates of national fuel consumption (Hughes, 1991; Thomas, et al., 2014).

The roof rack is one of the most common and popular accessories on U.S. vehicles (The Reynolds and Reynolds Company, 2014). A roof rack can be attached to a vehicle roof for occasional carrying of bicycles, skis, boxes, etc. Major brands of roof racks in the United States are Barrecrafters, Saris, Thule, and Yakima. The configurations of roof racks vary depending on the need but they always increase aerodynamic drag and cause vehicles to expend additional energy to achieve desired speeds. Aerodynamic drag (D) depends on four factors: projected frontal area (A); the drag coefficient (C_D); vehicle speed (V); air density (ρ), and is expressed as shown in Eq. (1) (Hucho, 1998).

$$D = \frac{1}{2}C_D \times \rho \times V^2 \times A \tag{1}$$

Based on the above equation, installation of a roof rack can increase aerodynamic drag by increasing both the drag coefficient (C_D) and the projected frontal area (A). Previous studies found that, for a car moving at 100 km/h, aerodynamic drag typically accounts for 75–80% of the total resistance, which is directly related to vehicle FC (Hucho, 1998; Juhala, 2014). Therefore, a roof rack (and the loads installed on it) will lead to a significant FC penalty on an individual vehicle. These individual vehicle impacts extend to the national fleet. Since leisure travel and spending are projected to rise in the United States (U.S. Travel Association, 2015), roof rack usage will most likely rise, too. This off-test fuel consumption, combined with widespread usage of roof racks, suggests a potential gap in our understanding of on-road fuel consumption. More detailed information can guide policies and regulations regarding roof racks for the purpose of reducing national fuel consumption and GHG emissions. Fuel consumption can also be reduced by improving the aerodynamic features of the racks. The technical potential from reduced drag appears to be large. One manufacturer (Whispbar, 2011) measured the aerodynamic drag forces of 12 different rack designs in a wind tunnel. It was found that the most slippery model had roughly 1/10 of the drag of the least aerodynamic model.

There has been relatively little published research on the fuel consumption penalties of roof racks. Two studies in 1985 and 1986 investigated FC impacts of roof-mounted light bars on police vehicles (Raub, 1985; Hansen and Blakenship, 1986). The roof-mounted light bar is a different application but has similar aerodynamics impacts. Adding roof-mounted light bars increased fuel consumption 7.1–12.7% when the vehicles were driven a constant 55 mph and 7.5% on overall driving miles (e.g., mixed speeds). Lenner (1998) investigated on-road impacts of roof racks for a 1992 Volvo 940 midsize sedan. The vehicle was equipped with an unloaded roof rack and driven at 43.5 mph, 49.7 mph and 55.9 mph. Fuel consumption increased 2.6%, 2% and 1.1% compared with a clean roof. When the roof rack was loaded with a ski box, fuel consumption increased 10%, 11% and 12.3% compared with the clean-roof conditions. The results were physically counter-intuitive in that the unloaded roof rack FC penalties actually decreased at higher speeds. Nevertheless, this was one of the first studies of FC impacts of roof racks and it illustrated measurement uncertainties in on-road studies. In contrast, Chowdhury et al. (2012) measured drag forces of passenger car add-ons through a series of wind tunnel tests. At high driving speeds ($>$80 km/h), the unloaded and loaded roof rack (carrying a ladder) resulted in 10–22% and 13–28% increases in aerodynamic drag depending on cross-wind effects and speeds. The drag forces can be translated into 7.5–17.6% and 10–22.4% increases in vehicle motion resistance and similar FC penalties. Chowdhury et al. estimated the combined FC penalty of installing all add-ons, but did not estimate the FC penalty for each add-on, such as a roof rack, towing trailer, etc. Thomas et al. (2014) adopted a similar methodology as Lenner (1998), but focused on evaluating FC penalties of different vehicle add-ons and modifications (i.e. low-pressure tires, open windows, roof top and hitch-mounted cargo, and trailer) through coast-down and dynamometer tests. The tests were conducted on popular vehicles. A rooftop cargo box significantly increased the vehicle's FC, but the magnitudes varied depending on the vehicle type and driving cycles. When a rooftop cargo box was installed on a Corolla sedan, FC increased 8.8% and 20.8% on city and highway driving cycles, respectively. For a Ford Explorer SUV, the FC penalties were 2.5% and 6.2% on the two driving cycles. The Thomas et al. (2014) study did not consider the FC penalty of an unloaded roof rack and the authors did not extrapolate the vehicle-level FC impacts to the national fleet. Other studies explored roof racks' impacts on design, noise, and forces (Jawad, et al., 2000; Lee, et al., 2002; Karbon and Dietschi, 2005; Senthooran, et al., 2007; Mandadapu et al., 2011).

In summary, previous studies using laboratory or on-road testing methods have explored roof rack FC penalties at a single-vehicle level, but they did not estimate national impacts on LDV fuel consumption. A national perspective is still needed to justify policy actions.

To fill this gap, we undertook a bottom-up study of national FC impacts of roof racks. The methodology integrates real-world experiments, field surveys, and a vehicle stock model to assess the roof rack FC impacts on the national LDV fleet. This approach differentiates roof rack FC impacts by vehicle type, driving situation (such as highway, urban driving) and utilization pattern (weekday and weekend). In addition, the methodology can be applied to estimate nationwide FC penalties of other LDV add-ons. This study's precision is inherently limited by the available data regarding FC penalties of specific rack configurations and the wide range of vehicle body styles, but the results are nevertheless meaningful and can inform policy-making. Furthermore, the methodology easily accommodates incremental improvements in input data as they become available.

The rest of the paper is organized as follows: methodology and data are discussed in Section 2. The results and sensitivity analyses are detailed in Section 3. The conclusion and policy implications are presented in Section 4.

2. Methodology

The purpose of this study is to create a methodology to estimate the incremental LDV fuel consumption caused by installation and usage of roof racks in the United States. Conventional modeling approaches and data are not appropriate here. For example, the sales of roof racks do not necessarily correlate with their installation and usage. The estimate is handicapped by lack of data at both the vehicle and national levels, including limited vehicle-level roof rack FC penalty information, lack of rack usage data, and absence of a suitable energy inventory model. Our approach addresses these challenges by collecting primary data through novel methods and building an energy inventory model tailored for the study. The methodological framework is shown in Fig. 1.

We first define the following index and set to be used in the study.