Fuel Consumption Impacts of Auto 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.

Keywords: Roof racks, fuel consumption impacts, energy modeling

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, 1992; 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 pre-determined cycles, such as the Federal Test Procedure, Highway Fuel Economy Test, US06, SC03, etc., on a chassis dynamometer (US EPA, 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.,

¹Light 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 8,500 pounds or less, before any after-market conversion to alternative fuel operation.

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 Equation 1 (Hucho, 1998).

$$D = \frac{1}{2} C_D \times \rho \times V^2 \times A \quad (1)$$

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 (US 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 (Whisbar, 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 at 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; Senthoooran, 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 Figure 1.

[Insert Figure 1 here]

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

Set name	Description
Y	Set of analysis year {2015,...2040}, indexed by y
I	Set of all vehicle types, indexed by i
C	Set of driving conditions {Highway, Non-highway}, indexed by c
R	Set of roof rack configurations as discussed in section 2.1, indexed by r
D	Set of day types {weekday, weekend}, indexed by d
Variable	Description
$V_FC_P_{i,c,r}^y$	Vehicle-level FC penalty by vehicle type i , driving condition c , and roof rack configuration r in each analysis year y .
$Freq_{c,r}$	Roof rack usage rates by driving condition c , and roof rack configuration r in each analysis year y .
VMT_i^y	Aggregated fleet VMT by vehicle type i and year y .
$VMT_Split_{c,d}$	VMY split among road condition and day of week.

$A_FC_R_{c,i}^y$	Average FC (Gallon / Mile) for vehicle type i , on driving condition c , at year y .
$T_FC_o^y$	Total LDV fleet FC in year y without considering roof rack FC impact
$T_FC_n^y$	Total LDV fleet FC in year y including roof rack FC impact

We first estimate vehicle-level roof rack FC penalties, $A_FC_R_{c,i}^y$, based on consumer-reported data (compiled from on-line forums) and limited test data from existing studies. In our baseline analysis, we assume the penalties do not change over time, but in later scenarios, we vary the penalty over time given assumptions of changes in rack design, government policies, etc.

Next, we estimate roof rack usage rates, $req_{c,r}$. These rates were based on nationwide highway video surveys conducted by the authors or workers recruited through Amazon Mechanical Turk². Note that rack usage rates were assumed to be the same for all vehicle types because we do not have enough observations to confidently estimate the differences.

Third, an energy inventory model was established to project the nationwide LDV roof rack FC penalty in current and future years. The model includes vehicle-level roof rack FC penalties, rack usage rates, vehicle stock, and vehicle miles travelled (VMT) through 2040. The national-level LDV fleet FC without considering roof racks at year y , TFC_o^y , is calculated by disaggregating VMT by vehicle type, road condition (highway and non-highway) and day of week (weekdays and weekends), and then multiplied by the associated vehicle FC rates (in units of Gallon / Mile), shown as follows.

$$TFC_o^y = \sum_{i \in I, y \in Y} \sum_{c \in C, d \in D} VMT_i^y * VMT_Split_{c,d} * A_FC_R_{c,i}^y$$

² Amazon Mechanical Turk is a on-line marketplace for tasks that requires human intelligence. It gives businesses access to a diverse, on-demand, scalable workforce and gives Workers a selection of thousands of tasks to complete whenever they choose.

The national FC is the sum of two parts. The first part represents the FC for vehicles without roof rack impacts, which is similar to the calculation process of TFC_o^y with exclusion of roof rack-related VMT. The second part represents the FC of vehicles with racks installed. These vehicles' FC rates will be increased by the roof rack FC penalties, shown below.

$$TFC_n^y = \sum_{i \in I, y \in Y} \sum_{c \in D, d \in D, r \in R} \{VMT_i^y * VMT_Split_{c,d} * (1 - Freq_{c,r}) * A_FC_R_{c,i}^y + VMT_i^y * VMT_Split_{c,d} * Freq_{c,r} * A_FC_R_{c,i}^y * (1 + V_FC_P_{i,c,r}^y)\}$$

Finally, the roof rack FC penalty at the national level at year y is calculated by:

$$FC\ Penalty^y = \frac{TFC_n^y - TFC_o^y}{TFC_o^y} \times 100\%$$

In the remainder of this section, we discuss the details of the framework, starting with the categorization of roof racks.

2.1 Roof Rack Categorization

We divided the many configurations of roof racks into three categories. These categories reflect their gross aerodynamic impacts. The categories are illustrated in Figure 2 and defined as follows:

[Insert Figure 2 here]

- 1) *Bare roof or roof with built-in rails.* Built-in rails run front to back, along the sides of a vehicle's roof. In most cases, the built-in rails are installed by the vehicle manufacturer and are part of a package. We assume this type of rack does not significantly influence vehicle FC. To be sure, built-in roof rails alter the vehicle frontal area and therefore can potentially increase aerodynamic drag force. However, the change in vehicle frontal shape is usually

small, in part because car manufacturers have been continuously improving the aerodynamics of built-in rails (Carr, 1976; Howard, 1986; Karbon and Dietschi, 2005; Kelly and Holcombe, 1964). In any event, the aerodynamic impacts of these racks are often already captured in fuel economy tests because they are part of many packages for new vehicles.

- 2) *Unloaded cross roof racks*. In this configuration, crosspieces are present to adapt the pre-existing roof rack to the specific application, such as carrying bicycles or skis. Additional hardware may be present to facilitate attachment. By “unloaded”, we mean the hardware is present for a specific application but no bicycles, skis, etc. are actually being carried. Consumers typically install crosspieces after they purchase the vehicles. Several previous studies have identified FC impacts of such roof racks or similar rooftop attachments in this configuration (Hansen and Blakenship, 1986; Lenner, 1998; Raub, 1985).
- 3) *Loaded cross roof racks*. In this configuration, bicycles, skis or other equipment are actually on the roof rack and being transported. Previous studies have found large FC penalties in this configuration, especially at higher speeds (Lenner, 1998; Thomas et al., 2014). This configuration covers a wide range of aerodynamic resistances and fuel impacts. For example, this configuration includes a bicycle rack with one, two, or three bicycles, a ski rack with snow boards or skis, and a luggage rack. It is not feasible to further differentiate this configuration due to lack of reliable data sources and the complexity of the problem.

2.2 Roof Rack Fuel Consumption Impact at the Vehicle Level

We utilized both consumer-reported and laboratory/on-road tested data to estimate roof rack FC penalties at the vehicle level. The FC penalties are expressed in relative terms (i.e. percentage

increase in FC compared with the no-rack condition). Hence, when available data were reported in absolute changes, we converted the results to relative changes. Consumer-reported data were collected through searching on-line forums. Car-owners often reported and discussed their observations of FC penalties on their vehicles after they installed racks. These drivers typically reported make/model of vehicles, recording date and time, road type, average driving speed, and FC penalties due to roof racks (see Supporting Information (SI) for reference). These self-reported data have obvious uncertainties, but these uncertainties are offset by the large number of measurements and wide variety of vehicles. For these reasons, these data can complement the laboratory or controlled on-road test data for more accurate estimates of fuel penalties.

The factors considered in the FC penalty calculation are rack configuration (unloaded/loaded cross roof rack), driving condition (highway, non-highway roads) and vehicle type (passenger car, passenger truck). There is an inherent uncertainty associated with this simple classification scheme. For example, items with different shapes can be loaded on a roof rack, vehicles can have different body styles and powertrain combinations, and driving patterns may differ. But the focus of this study is to provide a framework to quantitatively analyze roof rack FC penalties at a national level. We evaluated several scenarios in order to better understand the uncertainties described earlier. These are described below.

Unloaded racks on vehicles traveling at slower speeds. This situation corresponds to cars with empty racks driving around cities. For unloaded cross roof rack FC impacts on non-highway roads, no lab or on-road test data are available. Most consumer-reported data suggest no FC penalty for this type of configuration. Therefore, we assume 0% FC penalty due to unloaded cross roof racks on vehicles (passenger car, passenger truck) driving on non-highway roads.

Loaded racks on vehicles traveling at slower speeds. This situation corresponds to cars transporting bicycles or skis driving around cities. No consumer-reported data are available for loaded cross roof rack FC impacts on urban roads. Only two previous studies examined FC penalties of racks or similar roof-mounted items in non-highway driving locations. After a series of driving tests, a 7.5% FC increase was observed for a police vehicle with roof-mounted lights compared with the same vehicle with a bare roof (Raub, 1985). Thomas et al. (2014) reported an 8% FC increase for a passenger car and 2.4% for a passenger truck driving the Federal Test Procedure (FTP) driving cycle. The FTP driving cycle was adopted as the city fuel economy test by EPA (EPA, 2006). In this study, we use the FC penalties for unloaded racks in non-highway driving conditions developed by Thomas et al. (2014), that is, 8% for passenger cars and 2.4% for passenger trucks.

Loaded racks on vehicles traveling at highway speeds. Data from on-line forums are concentrated in this scenario. About 70% (18 observations out of 26) of consumer-reported data estimated loaded cross roof rack FC penalties between 20% and 30%. These observations seem to match results from Thomas et al. (2014) i.e., 24.8% FC increase at 70 mph constant-speed highway driving for passenger cars. Thomas et al. also reported an 11.7% FC penalty for a passenger truck under the same conditions. Lenner (1998) found fuel consumption increased 12.3% for a sedan with a roof rack and ski box travelling at 55.9 mph. An extrapolation of Lenner's result from 55.9 mph to 70 mph, gives a FC increase of about 20%. This is close to other studies as well as consumer-reported data. We adopted 24.8% as the FC impacts for passenger cars and 11.7% for passenger trucks driving on highways. These values from Thomas et al. (2014) are the most recent and based on the most comprehensive study.

Empty racks on vehicles driven at high speeds. About 84% (26 out of 31) of consumer measurements reported FC penalties due to unloaded cross roof rack between 5% and 15%. These results are not consistent with lab tests. One possible explanation for the discrepancy is that most drivers reported FC penalties in terms of MPG and they usually rounded the number up to the next integer. This reporting behavior potentially over-estimates the penalties. Two earlier studies found 1.1%~2.6% FC increases for a sedan travelling at 43.5~55.9 mph with an unloaded cross roof rack (Lenner, 1998) and 6.6%~11.3% increase for a police patrol vehicle travelling at 55 mph with different configurations of bar lights (Raub, 1985). Lenner (1998) showed that, when vehicle speeds were increased from 43.5 mph to 55.9 mph, the FC penalties actually declined from 2.6% to 1.1%. This inconsistency might be explained by the fact that fuel consumption and aerodynamic resistance of the rack do not increase at the same rate with speed. In our analysis, we assumed a 1.1% FC penalty for passenger cars with unloaded cross racks because this is a test-based result and is more relevant to our study. For passenger trucks, we applied the ratio between the two vehicle types from Thomas et al., that is, 11.7%/24.8%, to 1.1% and obtained 0.5% as the FC impact for passenger trucks during highway driving. These assumptions (for cars and trucks) are conservative because fuel impacts could be closer to consumer measurements.

2.3 Highway Video Surveys to Determine Roof Rack Usage Behavior

We undertook field surveys and collected available traffic camera videos to estimate real-world roof rack utilization. The videos mainly come from two sources: national highway monitoring videos, and private videos taken by authors or individuals through “Amazon Mechanical Turk”. In selecting traffic observation locations, we sought to cover many US metropolitan areas and to capture both weekday and weekend conditions. Figure 3 presents the locations, number of vehicles recorded and weekday (yellow) or weekend (purple) and other information about each video

sample. Each video recorded about 20 to 330 passing vehicles. We counted the vehicles with each type of roof rack configuration and tabulated the shares as discussed in section 2.1.

[Insert Figure 3 here]

The shares of vehicles with unloaded and loaded racks range between 1.5%~4.5%, and 0.2%~1.5% (see SI for reference). We aggregated all samples into a national average. The national averages of vehicles with cross roof racks are 3.0% on weekdays, and 2.5% on weekends. For vehicles with loaded cross roof racks, the average number is 0.5% on weekdays and 0.9% on weekends. Higher percentages of vehicles with loaded roof racks were observed during weekends compared with weekdays; this is inconsistent with the expectation that people transport more recreational equipment during weekends. These values were used to estimate national roof rack FC impacts. Note that the usage data are not differentiated by road type because the sample sizes were not large enough to make confident inferences. Our work, however, demonstrates that larger sample sizes could be acquired quickly and inexpensively. Since the focus of this study is to demonstrate a methodology, we used the above data and conducted sensitivity analyses to understand the uncertainty.

2.4. Input Data

Inputs for our study came from primary and secondary data sources described above. Other input data were obtained from the Annual Energy Outlook 2015 (EIA, 2015), the Bureau of Transportation Statistics (Bureau of Transportation Statistics, 2015), and default values from EPA's Motor Vehicle Emission Simulator (Environmental Protection Agency, 2009).

Two types of vehicles were considered, passenger cars and passenger trucks. Within each vehicle type, several powertrains (such as gasoline vehicles, different types of electric vehicles, hydrogen

fuel cell vehicles) are included. These categories are consistent with definitions in the 2015 Annual Energy Outlook (or AEO) (EIA, 2015). The total US LDV fleet VMT is based on AEO 2015 reference case. The AEO reference case disaggregates VMT by vehicle technology type for each year from 2015 to 2040 (EIA, 2009). These were also used. The VMT distributions, broken down by geography (highway, non-highway roads) and time (weekdays and weekends) are obtained from MOVES national default values (Environmental Protection Agency, 2009). The average FC per distance for each powertrain from 2015 to 2040 comes from Annual Energy Outlook 2015 (EIA, 2015). MOVES default values as well as other VMT and fuel consumption data are used to calculate fuel consumption per distance on highway and non-highway roads (Bureau of Transportation Statistics, 2015; Environmental Protection Agency, 2009; ORNL, 2014). The roof rack vehicle-level FC impacts and utilization patterns are based on existing literature, website searches and field surveys as described previously (see base case definition in Table 1).

3. Results

3.1 Roof Rack Fuel Consumption Penalty in Base Case

Based on the model and input data described above, we estimate the US nationwide FC penalty due to roof rack usage. Figure 4 shows the roof rack FC penalty relative to total US annual transportation FC (left axis) and in actual gasoline gallon equivalent (GGE) (right axis). Roof racks increased national fuel consumption by about 0.81‰ in 2015. The penalty rises to 0.84‰ in 2040. The fraction initially decreases from 0.81‰ in 2015 to 0.78‰ around year 2018 and remains constant between 2018 and 2025. After 2025, the fraction increases again. This U-curve is caused by modeling assumptions regarding VMT and vehicle mix. Roof rack FC penalties for passenger cars are (relatively) higher than those for passenger trucks. When passenger cars are responsible for a larger share of distance travelled (compared to passenger trucks), the LDV fleet

rack FC penalties relative to total transportation FC will be increasing, and vice-versa. The AEO (2015) predicts that total VMT for passenger cars will decrease and reach a minimum around 2024; after that it will climb until 2040. This trajectory matches the trend of roof rack FC penalties perfectly. The actual quantities of fuel consumed due to roof racks gradually decline, starting from 107 million to 90 million gasoline gallons equivalent in 2040. This decline is a consequence of long-term reductions in LDV fleet consumption assumed in the model (AEO, 2015).

[Insert Figure 4 here]

The results shown in per mile format are not sensitive to different mixes of advanced technology vehicles in the fleet because the vehicle-level roof rack FC penalty is defined as a relative term (i.e., % more fuel consumed due to use of racks). In fact, the absolute size of the fuel penalty will decline when more energy efficient vehicles enter the fleet.

3.2 Sensitivity Analysis of Parameters Related to Roof Racks

As discussed in the methodology section, there exist significant uncertainties in roof rack usage patterns and vehicle-level FC penalties. We performed sensitivity analyses to understand the variation of roof rack FC penalties with changing input parameters. Here, vehicle-level roof rack FC penalties and usage pattern parameters were increased 20% in each scenario. We show only the positive change results (see Figure 5) because the absolute values do not change for 20% increase or decrease of these parameters. The biggest difference (12% increases) arises from changing the FC penalties for unloaded cross roof racks on highway driving conditions. The smallest difference (0.8% increase) occurs by changing FC penalties of loaded roof racks on non-highway driving. This difference arises because the VMT for vehicles with unloaded racks is 4~8 times higher than that of vehicles with loaded racks. Hence, a change in the FC penalty for vehicles with unloaded

racks will be applied to more VMT and result in higher FC penalties. Note that no sensitivity analysis was conducted for unloaded roof rack FC impact on urban roads because both consumer-reported data and on-road test data support our original assumption. For rack usage parameters, increasing unloaded weekday rack usage by 20% causes the highest percentage change (9.6%) whereas the minimum change (2.7%) is obtained by increasing loaded roof rack usage on weekends. This result can be explained by the fact that the 5 weekdays account for over 70% of total VMT. In summary, the most influential parameters are related to unloaded roof rack FC penalties and weekday usage patterns. These results suggest that some fuel-saving policies should focus on reducing the number of vehicles driving with empty racks.

[Insert Figure 5 here]

Another aspect of uncertainty lies on the distance traveled by vehicles with roof racks. Studies have shown that people who like outdoor activities travel more (Clawson and Knetsch, 2013). It is likely that people who install roof racks on their vehicles are outdoor-oriented as well. Hence, the average VMT for vehicles with racks are higher than vehicles without racks. To assess the uncertainty of the VMT input parameter, we assume vehicles with racks have 5%~20% higher VMT than normal vehicles. There are two ways of implementing these assumptions in the model. One way is to change the VMT mix but keep the LDV fleet total VMT unchanged. Another way is to increase the total LDV fleet VMT by increasing the VMT of vehicles with racks but keeping the VMT of normal vehicles unchanged. Increasing the VMTs 5%~20% for vehicles with racks leads to a 0.008‰~0.03‰ increase in roof rack FC penalties relative to total transportation FC. The second approach, increasing LDV fleet total VMT, increases penalties 0.04‰~0.15‰. Either way, the overall impact is negligible.

3.3 Impacts of Future Government Policies and Changes in Consumer Behavior

We conducted additional analyses to evaluate the impacts of government policies or changes in consumer behavior. In the earlier analyses, we assumed constant rack FC penalty and usage parameters until 2040 (see Table 1). But here we change the parameters to examine impacts of various policies.

As the US economy continues growing and more people participate in outdoor activities, both sales and usage of roof racks will increase (The Reynolds and Reynolds Company, 2014). The US Travel Association projected that domestic personal travel expenditure in US will increase by 53% from 2011 to 2020, equivalent to 4.3% average annual growth rate (US Travel Association, 2015). By applying the same growth rate, the usage of roof racks will increase by about 200% by 2040. We call this scenario “More Travel”. This scenario is a reasonable benchmark value to estimate future roof rack FC penalties even if the increases in actual rack usage do not perfectly track domestic travel expenditures.

Government policies might be enacted to assist consumers in the purchase and operation of roof racks. For example, energy labels (such as those for air conditioners and light bulbs (Olofsson, et al., 2004)) could help consumers understand the extra fuel costs resulting from using roof racks and nudge consumers towards the most aerodynamically efficient units. Energy labeling programs for appliances are typically inexpensive to implement and often stimulate significant market transformations. These policies may also encourage manufacturers to produce more efficient racks to avoid being identified with selling a low-quality product. We examined the impact of a policy that caused more aerodynamic roof racks to be marketed and purchased. We modeled this as a gradual reduction of roof rack vehicle FC penalties by 50% by 2040. This seems easily achievable

given the wide range in efficiencies of current models. We call this scenario “ImprovedEff. Roof Rack”.

Other policies might facilitate installation and removal of racks so that vehicle owners will remove them when not actually transporting bicycles, skis, and other goods. The extreme policy would be a prohibition of driving with empty racks, which would be both unrealistic and difficult to enforce. We modeled this policy as gradually reducing driving with unloaded cross roof racks on both highway and non-highway roads to 0% by year 2040, and call this scenario as “Banned Unloaded RR”. We also examined other scenarios by combining any of two or three of the defined three scenarios. A summary of the scenarios and their descriptions are shown in Table 1.

[Insert Table 1 here]

This scenario “Improved Eff. RR + Banned Unloaded RR” leads to the lowest FC penalties arising from roof rack usage. Compared with the base case scenario, a total of 200 million GGE can be saved during the model timeframe of 2015 to 2040. In addition, compared with worst scenario “More Travel”, “ImprovedEff. RR + Banned Unloaded RR” has potential cumulative savings of 1.2 billion GGE over the 26 years. “Banned Unloaded RR” achieves the second highest reduction in the roof rack FC penalty, followed by the case “Improved Eff. RR”. The scenarios again confirm that reducing usage of unloaded roof racks will save more fuel compared with improving roof rack energy efficiency, but only if a successful policy to radically transform driver behavior can be implemented. In summary, if no policies are launched to improve aerodynamic efficiency of racks and to reduce driving with empty racks, we can expect increasing fuel consumption caused by roof racks.

[Insert Figure 6 here]

3.4 Discussion

The additional fuel use arising from use of roof racks is uncertain because an estimate requires information about the number of racks in actual use as well as the FC penalty at the single-vehicle level. To overcome the data gaps, we used novel sources for data collection, such as online forums and crowd-sourcing (Amazon Mechanical Turk). Our observations show that 3.0% and 2.5% of vehicles are being driven with empty roof racks during weekdays and weekends, respectively. Only 0.5% and 0.9% of the vehicles have loaded racks on weekdays and weekends, respectively. Loaded racks were observed more often during weekends, presumably because more people carry recreational equipment for leisure use on weekends. The novel data collection techniques used in this analysis have potential applications in other situations where national surveys are required. Amazon Mechanical Turk is especially intriguing because it enables surveys to be performed around the country quickly and at low costs.

We find consistent estimates of FC penalties across laboratory tests, on-road tests, and consumer-reported data. Depending on the roof rack configuration (unloaded or loaded cross roof rack) and driving condition (highway or urban roads), a roof rack can increase a passenger car's fuel consumption 0%~25% and a passenger truck's consumption and 0%~11.7%.

Based on our modeling results, roof racks are responsible for an additional 90~107 million GGE per year between 2015 and 2040, which are about 0.78%~0.84% of LDV fleet FC. Sensitivity analyses on input parameters indicate that parameters related to usage (particularly unloaded cross roof rack usage on weekdays) most strongly affect total fuel penalties. This finding clearly points out that

policies seeking to reduce fuel consumption from roof racks should focus on vehicles being driven with unloaded racks on weekdays, although it's not clear how these behavior changes would be—or could be—implemented. On the other hand, the results do not significantly change if vehicles with roof rack are driven more than average vehicles.

4. Conclusion and Policy Implications

This is the first attempt to quantitatively and systematically evaluate national FC penalties of roof racks. It is important to assess the additional FC caused by the usage of roof racks because they are one of the most popular add-on components in the U.S. automobile market. Our results show that roof racks are responsible for 0.78‰ to 0.84‰ of US transportation FC in the next two decades. However, the absolute fuel penalty will decline from 107 million to 90 million GGE from 2015 to 2040 as more energy efficient vehicles penetrate the market. Sensitivity analyses demonstrated the robustness of these results. Our proposed framework can also quantify FC impacts of other after-market automobile components.

Roof racks raise national fuel consumption by only about 1‰, which is about 100 million GGE per year. It is useful to put this 1‰ in context of other national policies. Fuel cell electric vehicles and battery electric vehicles have received considerable federal attention and support. For comparison, the additional fuel consumption caused by roof racks is about 6 times larger than anticipated fuel savings from fuel cell vehicles and 40% of anticipated fuel savings from battery electric vehicles in 2040³. In addition, the FC penalty is easily detected by all drivers with roof racks. Government policies could address this issue. For example, energy labels could guide consumers towards the

³ AEO 2015 reference case projected 1.07 million and 0.06 million battery electric vehicles and fuel cell electric vehicles existing in the vehicle stock in United States. Assuming average annual VMT is 13350 miles (Stephens, 2014) and average fuel economy of conventional gasoline vehicles fleet is 52 MPG (EIA, 2015), the fuel savings achieved by battery cell electric vehicles and fuel cell electric vehicles are 259 million and 15 million GGE respectively.

most aerodynamic racks and encourage manufacturers to improve efficiencies of their products.

Additional policies could facilitate, or even mandate, removal of racks when they are not actually in use. Anticipated growth in rack usage makes such policies even more important. We created scenarios covering possible outcomes from implementing these policies as well as a possible increase in future use. The combined strategy of aerodynamic improvements and eliminating driving with empty (unloaded) racks will achieve the lowest roof rack FC penalty. A cumulative saving of 1.2 billion GGE can be saved compared with the base case over the next 25 years. Eliminating unloaded cross roof racks is a more effective strategy, compared with increasing the energy efficiency of roof racks, because vehicles with unloaded cross roof racks account for 4~8 times more VMT (hence, more fuel consumption) than vehicles with loaded racks. From a practical perspective, however, improving the aerodynamics of new racks may be simpler to accomplish than changing behavior.

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Table 1. Scenario dues to different government policies and consumer behaviors

	RR Veh. Level FC*	Loaded RR Usage*	Unloaded RR Usage*
Base Case*	PC: Highway-Unload RR: 8% Highway-Loaded RR: 24.8% Nonhighway-Unloaded RR: 0% Nonhighway-Loaded RR: 1.1% PT: Highway-Unload RR: 2.4% Highway-Loaded RR: 11.7% Nonhighway-Unloaded RR: 0% Nonhighway-Loaded RR: 0.5%	Weekday: 0.5% Weekend: 0.9%	Weekday: 3.0% Weekend: 2.5%
More Travel	No change	Gradually doubled from 2015 to 2040	Gradually doubled from 2015 to 2040
Improved Eff. RR	Gradually reduced by 50% from 2015 to 2040	No change	No change
Banned unloaded RR	No change	No change	Gradually eliminated from 2015 to 2040
More Travel + Improved Eff. RR	Gradually reduced by 50% from 2015 to 2040	Gradually doubled from 2015 to 2040	Doubled from 2015 to 2040
More Travel + Banned unloaded RR	No change	Gradually doubled from 2015 to 2040	Gradually eliminated from 2015 to 2040
Improved Eff. RR + Banned Unloaded RR	Gradually reduced by 50% from 2015 to 2040	No change	Gradually reduced to 0% from 2015 to 2040
All three	Gradually reduced by 50% from 2015 to 2040	Gradually doubled from 2015 to 2040	Gradually eliminated from 2015 to 2040

*Unless specified, parameters defined in scenarios remain the same for all analysis years, 2014 to 2040.

Figure 1. Framework for estimating nationwide fuel penalty caused by passenger vehicle roof racks.

Figure 2. Examples of different roof rack configurations. Upper left: Roof with built-in rails (from Thule); Upper right: Unloaded cross roof rack (from Thule); Lower: Loaded cross roof rack (Thomas et al., 2014).

Figure 3.Video Survey Sampling Locations and Number of Observations.

Figure 4. Roof Rack FC Penalty Relative to Total LDV Fleet FC (left axis) and in GGE (right axis)

Figure 5. Sensitivity of Input Parameters to Roof Rack FC Penalty.

Figure 6. Results under Various Government Policies and Consumer Behavior Scenarios.