

**VEHICLE FUEL ECONOMY AND THE REBOUND EFFECT – AN ANALYSIS OF  
EFFICIENCY**

By

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## **LIST OF ABBREVIATIONS**

ANOVA – Analysis of variance

CAFE – Corporate Average Fuel Economy

CI – Confidence interval

CO – Carbon monoxide

CO<sub>2</sub> – Carbon dioxide

DOE – Department of Energy

EPA – Environmental Protection Agency

CH<sub>4</sub> - Methane

GHG – Greenhouse gas

cm – centimeter

gal – Gallon

GPS – Global positioning system

REET – Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation

HEV – Hybrid electric vehicle

HMT – Household miles travelled

ICE – Internal combustion engine

IRB – Institutional Review Board

kg - Kilogram

LCA – Life cycle assessment

LT – Long term

m - Meter

MJ - Mega joule

mpg – Miles per gallon

MSA – Metropolitan statistical area

MMSA – Madison Metropolitan Statistical Area

N<sub>2</sub> – Nitrogen gas  
N<sub>2</sub>O – Nitrous oxide  
NA – Not applicable  
NHTS – National Household Transportation Survey  
NHTSA – National Highway Traffic Safety Administration  
NO<sub>x</sub> – Nitrogen oxides  
O<sub>3</sub> – Ozone  
Pb – Lead  
PM – Particulate matter  
PUT – Pickup truck  
SO<sub>x</sub> – Sulfur oxides  
ST – Short term  
SUV – Sport utility vehicle  
US – United States  
VOC – Volatile organic compound  
WHO – World Health Organization  
WI – Wisconsin  
WTP – Well to pump  
WTW – Well to wheel

## **SUMMARY**

Understanding and quantifying the environmental impacts of personal transportation is the first step in the management and mitigation process. A life cycle assessment of vehicles allocates a sweeping majority of the lifetime environmental impacts to the use phase. This justifies the strong emphasis being placed on development of fuel efficient vehicles as the chief method used to reduce the environmental impact of transportation. When mandating widespread adoption of efficient vehicles, it is important to consider the rebound effect, a deliberation that is often overlooked. The rebound expresses an increase in consumption associated with an increase in efficiency. A consensus in the literature produces a rebound for improving vehicle fuel economy around 20%, though a fair degree of variability does exist, ranging generally from 5%-65%, with one study presenting value of 1000%.

This study investigated how consumers will alter their driving habits in response to changes in fuel price, in the form of both price fluctuations at the pump and improvements in fuel efficiency. Data were also analyzed from four years of the National Household Transportation Survey spanning from 1990 to 2009 and one firsthand survey to estimate the environmental impact of personal vehicle usage, changes in driving behavior over time, and the extent to which a rebound may be exhibited following the adoption of fuel efficient vehicles. The environmental impacts were assessed over the impact categories of energy, water consumption, and emission of multiple different pollutants. Results were obtained for the state of Wisconsin; the Milwaukee, WI, region; and the Madison, WI, area.

It was found that there was no difference significant between the groups for annual household miles travelled and for the size of fuel price increase to provoke a change in driving tendencies.

There was, however, a difference in how each group would respond to the identified fuel price change. The analysis of environmental impact concluded that in the entire state of Wisconsin, eight of the ten impact categories exhibited a decrease in per person impact between the survey years. In Milwaukee, WI, all ten impact categories displayed an increase in per person impacts. Coincident with a generally increasing trend in annual miles driven per person, improvements in fuel efficiency may not have been the influential factor in decreasing the impacts. The myriad rebound calculations produced magnitudes between 30%-846%, appreciably larger than the 20% approximate average value found in the literature. This suggests that consumers who adopt more fuel efficient vehicles may have a strong propensity to increase their driving activity to the degree that their increase in consumption more than out paces the increase in efficiency, resulting in an overall increase in environmental impact despite improving efficiency.

## **1.0 INTRODUCTION**

The past half-century has witnessed increasing awareness and concern for environmental quality and protection (Dunlap & Mertig, 1991). Environmental legislation in the United States began to be introduced in the late nineteenth century with the 1899 Refuse Act, which banned dumping refuse into navigable waterways (U.S. Environmental Protection Agency, 2016), while the creation of the Environmental Protection Agency (EPA) in 1970 led to additional laws that regulate water quality, hazardous wastes, resource disposal and recovery, and air quality (U.S. Environmental Protection Agency, 2016). One of the forefronts of present-day environmental apprehension is a changing climate due to rising atmospheric concentrations of carbon dioxide (CO<sub>2</sub>) and other greenhouse gases (GHGs). A consensus in the scientific community determined that human activity is the primary driver of modern climate change through emissions of anthropogenic GHG (Rosenzweig et al, 2008).

Partitioning of current GHG emissions by source identifies the transportation sector as emitting approximately 25% of global GHG (Archer, 2012), the majority of which is attributed to personal automobiles (Maclean & Lave, 2003). Significant efforts have been made to reduce on-the-road impacts, such as producing vehicles with improved fuel economy, allowing drivers to consume less fuel to travel a given distance (U.S. Department of Energy, 2015). Consumer demand for fuel efficient vehicles has also been on the rise, and ownership of hybrid vehicles has become more widespread (Heutel & Meuhlegger, 2015). The essence of producing fuel efficient automobiles is to reduce the environmental impact generated by transportation, but it is appropriate to investigate the extent to which adoption of a fuel efficient vehicle may change

consumers' driving behavior in order to develop a clear understanding of the realized change in environmental impact.

## **1.1 RESEARCH SUMMARY AND GOALS**

The overall objective of this research was to investigate the extent to which adoption of fuel efficient vehicles influences consumer driving behavior and to assess the resulting environmental repercussions. A life cycle assessment (LCA) approach was the chief means of analyzing the use phase sustainability of vehicle fuel economy improvements.

This research sought to compare the changes in environmental impacts associated with efficiency changes with those values found in the literature to help build the scientific knowledgebase on vehicle sustainability and the rebound effect. This was accomplished through investigation into consumers' anticipated changes in driving tendencies due to changes in fuel price and consumer valuation of various vehicle attributes (Chapter 2), along with transportation use phase environmental impact change over time and its connection with the rebound effect (Chapter 3).

## **1.2 OBJECTIVES**

The underlying motivation for this research was to assess the use phase environmental impact of personal transportation and how particular consumer behaviors alter the impacts. Of particular interest was the degree to which drivers changed their number of miles driven in response to adopting a vehicle that was more efficient than their previous vehicle. An in-depth assessment of this research topic was completed by accomplishing the following objectives:

- 1) Understand consumer motivations for purchasing a vehicle by collecting ranking of importance of certain vehicle attributes through an administered survey.

- 2) Investigate consumer responses to increases in fuel price via estimates of the size of per unit fuel price increase which would instigate changes in driving behavior and identification of what are those changes.
- 3) Model the use phase environmental impacts of personal transportation and the extent to which that changed over time and space.
- 4) Explore the magnitude of the rebound to probe consumers' propensity to increase their consumption and the associated impact coincident with adoption of fuel efficient vehicles.

### **1.3 LIFE CYCLE ASSESSMENT**

The life cycle of all products processes has four general stages, typically identified as acquisition of raw materials, production or manufacturing, use, and end of life (Graedel & Allenby, 2009). Each phase produces a particular set of environmental impacts, and life cycle assessment (LCA) is a methodical instrument used to identify the impacts generated by a product or process over its entire lifetime. An LCA identifies the separate life cycle stages and the impacts associated with each stage. This can outline points throughout the life cycle where the largest impacts are generated and where a reduction in environmental impact may be achieved without merely shifting the environmental load to a different life cycle stage—a concept known as hotspot analysis. LCAs are assessed over identified impact categories which can include pollutant(s) emitted, resources used (water, trees, or energy), or waste generated (Carnegie Mellon University, 2015).

An LCA of automobiles reveals that a majority of lifetime GHG emissions are produced during the use phase, where use phase impacts of automobiles are comprised of tailpipe emissions, fuel cycle impacts, and non-tailpipe emissions such as brake and tire wear and automotive fluid leakage (Castro et al, 2003). Helms et al (2010) presented the use phase as being accountable for 75% of vehicle lifetime emissions. Maclean & Lave (2003) also found the use phase to produce approximately 75% of lifetime vehicle GHG emissions. Schafer et al (2006) identified 90% of lifetime vehicle GHG emissions as being attributed to the use phase for internal combustion engine (ICE) vehicles. Samaras & Meisterling (2008) obtained values for ICE vehicles and hybrid electric vehicles (HEVs) and found use phase impact values for both technologies to be approximately 87%, indicating battery production in HEVs has a negligible impact compared to the use phase. These studies provide a sample of the consensus in the literature that the use phase imparts the largest environmental impact for automobiles.

Understanding that a strong majority of impacts are produced in the use phase, it stands to reason that the greatest impact reductions can be attained by targeting the use phase. Thus, it can be rationalized that this phase should receive the largest focus to reduce automobile impacts.

Similarly, focusing impact reduction efforts on other processes in the life cycle—such as resource extraction and refinement, battery production, and factory vehicle production—is likely to yield diminishing impact reductions based on the small portion of lifetime impacts associated with those life cycle stages. Since a large portion of the use phase impacts are derived from the fuel production cycle and the combustion of fuel, efforts to reduce fuel consumption appear to be a viable method for most effectively reducing transportation environmental impacts. This may justify the national push improve vehicle fuel economy in an attempt to reduce fuel consumption.

#### **1.4 TRANSPORTATION EVOLUTION AND POLICY**

Numerous measures have been taken to reduce fuel consumption from transportation (Schafer & van Basshuysen, 1995). Two predominant sets of ideologies exist that attempt to bring about this reduction: market manipulation through taxes on fuel and/or fuel-inefficient vehicles and technological advancements that improve vehicle fuel efficiency (Sterner & Kohlin, 2012). Artificially increasing the price of fuel via a tax theoretically decreases fuel consumption based on the rudimentary supply and demand economic principle, where an increase in price spurs a decrease in demand (Mankiw, 2014). By consuming less fuel, it is thought that transportation-associated environmental impacts will subsequently decrease. Similarly, raising the price of fuel-inefficient automobiles by means of taxation generates a disincentive to purchase such vehicles, which should promote adoption of fuel efficient vehicle on economic grounds.

The other school of thought is to technologically improve automobile fuel efficiency, largely with a top-down approach of legislation and policy. This strategy has been the method of choice in the United States, where the Corporate Average Fuel Economy (CAFE) standards are the main set of fuel economy policies (McConnell, 2013; Austin & Dinan, 2005). Initially enacted in 1975, the CAFE standards sought to reduce energy consumption via fuel economy improvements in cars and light trucks (National Highway Traffic Safety Administration, 2016). CAFE standards have improved over time, and The National Highway Traffic Safety Administration (NHTSA) has issued a new set of standards to swiftly increase fleet efficiency with the next decade (NHTSA, 2016). With vast attention being paid to improving fuel efficiency, it becomes relevant to understand how consumers' driving behavior may change in response, and whether it may lead to an increase in driving.

## **1.5 REBOUND EFFECT**

In 1865 English economist William Stanley Jevons observed that efficiency improvements in steam engine coal combustion in London led to an increase in coal consumption, not a decrease as was anticipated (Alcott, 2005). As outlined in *The Coal Question* by Jevons (1866), he postulated that consumption levels would not change as steam engine coal combustion improved in efficiency, and consumption of coal as a fuel source would decrease. This oversight did not account for peoples' propensity to increase their consumption of travel in response to the less expensive cost per unit of energy. Jevons rather posited that consumers did not merely increase their energy consumption, they did so to such a degree that their change in consumption outpaced the change in efficiency, which led an increase in air pollution and other environmental impacts resulting from the increase in efficiency (Jevons, 1866). This general interplay of increased consumption with increased efficiency has been generalized into a phenomenon called the rebound effect, and the specific dynamic Jevons observed where change in consumption outpaced change in efficiency has been coined backfire.

The rebound effect can take myriad different forms, but it is generally defined as an increase in demand for a product or service due to a decrease in per-unit price of that product or service through improved efficiency (de Haan et al, 2006). Rebound values are expressed as a percentage, which reflects the percent of anticipated environmental impact reduction that has been eroded by the increase in consumption. A value between zero and 100% implicates an overall savings, while a value exceeding 100% connotes a net increase in impacts—the condition observed by Jevons, known as backfire (Hertwich, 2005). In the context of automobile fuel efficiency, a rebound less than 100% corresponds to an increase in miles driven, yet a decrease in fuel consumed. This occurs when the percent increase in efficiency is larger than the percent increase in miles driven and results in an erosion of the expected impact savings or reduction; a

rebound of 20% corresponds to only 80% of the anticipated savings being realized. When backfire occurs with respect to vehicle efficiency, the result is an increase in both miles driven and fuel consumed, where the percent change in consumption exceeds the percent change in efficiency and net impact increases.

Understanding the rebound and how it applies to adoption of fuel efficient vehicles can help determine whether the anticipated environmental impact reduction is partially or completely eroded. An accurate rebound quantification can model the extent to which this erosion occurs, which can ultimately shed light on the efficacy of policies like the CAFE standards. A small rebound suggests efficiency standards may be effective in reducing fuel consumption and transportation environmental impacts, while a large rebound implicates increases in efficiency spur large increases in consumption.

**2.0 REBOUND EFFECT IN FUEL EFFICIENT VEHICLES – AN ANALYSIS INFORMED BY  
LITERATURE AND SURVEY DATA**

The following chapter is a reproduction of an article as submitted to the Journal of Energy Efficiency, with the citation:

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This article appears as prepared for submission, although style and formatting modifications have been made.

## 2.1 INTRODUCTION

One of the pressing problems facing humanity in the 21<sup>st</sup> century is a changing climate. Decades ago the leading cause of climate change was unclear, however current science suggests that anthropogenic actions are the overwhelming culprit (Herbert, 2007). Since modernization during the Industrial Revolution, human society has made marked growth in agriculture, power production, and industry, as well as in infrastructure via booming economic urban centers and wide-reaching transportation networks (Fagerberg, 2000). Although these advancements deliver large benefits such as increased life expectancy and improved quality of life, they all also impart various significant economic, environmental, and social costs (Lindert & Williamson, 1983). The heartbeat of each of these activities is driven by the use of fossil fuels and produces the vast majority of anthropogenic greenhouse gas emissions (Archer, 2012), with the transportation sector emitting approximately a quarter of all emissions (Maclean & Lave, 2003) and passenger vehicles contributing the largest sub-portion (Kotval-K & Vojnovic, 2016).

There are two main methods used to arrest and ideally reverse the quantity of energy consumed and the increasing levels of GHG emissions from transportation: a market-based approach of increasing fuel prices by way of a fuel tax and legislation requiring new vehicles to meet a particular fuel efficiency standard (Clerides & Zachariadis, 2008). The economic principle behind a fuel tax is to increase price for fossil fuels or fuel-inefficient vehicles and create a consequent decrease in demand for those goods. This will result in fewer miles driven, less fuel consumed, and lower levels of emissions. Alternately, producing vehicles with improved fuel efficiency will allow consumers to travel a given distance using less fuel, also theoretically decreasing emissions.

An important consideration while quantifying the fuel savings from producing increasingly fuel efficient vehicles, however, is determining the rebound effect. This work will present a review of the literature followed by the results from a survey probing changes in consumer driving habits due to increased fuel efficiency and vehicle purchasing motivations. Of particular interest in this research is how a potential rebound varies between subjects residing in urban regions and their suburban counterparts.

## **2.2 EVALUATION OF THE LITERATURE ON VEHICLE FUEL EFFICIENCY REBOUND EFFECT**

### *2.2.1 THE REBOUND EFFECT*

The concept of the rebound effect is rooted in the Jevons Paradox, which was developed by William Stanley Jevons in 1865. He stated that increased efficiency and profitability of burning coal in Britain would lead to increased coal consumption (Alcott, 2005; Jevons, 1866). The Jevons Paradox aims at an extreme effect, today known as backfire, where the increase in efficiency leads to an overall increase in the total amount of the resource used (Polimeni et al, 2008). The notion behind the Jevons Paradox has been generalized into the rebound effect to pertain to the efficiency/consumption relationship of myriad goods. The rebound effect spans beyond backfire conditions to also encompass occasions where per unit consumption rises while total consumption decreases. This dynamic can be observed with automobile fuel efficiency and fuel consumption, where an individual increases his number of miles driven but decreases the amount of fuel consumed. This can be illustrated by increasing fuel economy by a larger margin than the resulting margin of increase of miles driven, which results in a net reduction of fuel consumed while increasing miles driven. For example, increasing fuel economy by 100% (doubling fuel efficiency) while increasing miles driven by 50% produces an overall decrease in

fuel consumed. Although there would be a net savings, this 50% increase in consumption will erode some of the anticipated energy savings associated with the efficiency increase.

The definition of rebound effect can vary, however the definitions used in this work will reflect those presented in de Haan et al (2005). De Haan et al (2005) identified a direct rebound effect as an increase in demand for a product or service as the price of that product or service decreases through increased efficiency. The indirect rebound effect exhibits an increase in demand for other goods and services as consumers experience an increase in their purchasing power (have more money to spend) due to an increase in efficiency and thus a decrease of cost of another product or service. Accurately estimating the rebound effect as it applies to improved fuel efficiency in vehicles will show what percentage of the theoretical fuel savings from increased efficiency is realized. This determination will offer insight into whether efficiency regulations will in practice lead to an overall fuel savings.

Within the context of fuel efficient vehicle adoption, a small rebound indicates that an increase in efficiency led to merely a small increase in miles driven, implicating a large overall consumer fuel savings. Conversely, a large rebound relates to a large increase in miles travelled due to the increase in vehicle efficiency, and thus a small overall savings of fuel (Greening et al, 2000).

Translating a quantified rebound estimate into a practical application, a large rebound would suggest that regulations mandating fuel efficient vehicles might not achieve the overall emission reduction goal due to the large resulting increase in miles driven; a small rebound would indicate emissions savings can be had through efficiency regulations (Fronzel et al, 2012). Currently the regulatory method has been the most widely used approach in the United States (Greene et al, 1999). A chief set of policies to accomplish this are the Corporate Average Fuel Economy

standards, which sets fuel efficiency standards for vehicle fleets and financially penalizes non-compliance (Austin & Dinan, 2005).

### *2.2.2 REBOUND ESTIMATES IN PRIOR STUDIES*

In general, the rebound effect for personal transportation has been calculated to be within the range of 5% to 65% (Binswanger, 2000), with most findings suggesting a value near 20%.

Frondel et al (2012) estimated a rebound effect at the upper end of this range at a value of 57% to 62%, which was recognized to be “substantially larger than those obtained from other studies”.

Greene et al (1999) found an estimate of about 10% in the short run (one year) and 20% in the long run, stated as being consistent with other studies. The values in Greene et al (1999) directly align with Greening et al (2000), in the 10% to 30% range over the short- and long-run, respectively. Binswanger (2000) determined the rebound effect to fall in the broad range of 5% to 50%, depending largely on the method employed in the respective studies. Clerides and Zachariadis (2008) deemed it rational to use a rebound of 20%. Reviewing the literature suggests that the large range found is due to a variety of factors such as location of study, methodology, and composition of research subjects.

Saunders (2000) found a consensus in the literature of vehicle fuel efficiency rebound effect to be relatively small, ranging from 5% to 10%. A subsequent study (Saunders, 2013) showed a slightly larger rebound with the short term rebound (ST) at 25% and long term rebound (LT) of 29%, where short term is defined as less than one year and long term is longer than one year.

Saunders (2013) also provided a larger-scale view of the rebound effect by quantifying it for 30 U.S. sectors. In comparison with vehicles, electric utilities exhibited an ST of 378% and LT of 120%, agriculture showed an ST of 79% and LT of 39%, and electronics had an ST of 26% and

LT of 41%. The overall rebound across the analyzed sectors was ST of 126% and LT of 62%. These are relatively large values and indicate a propensity of consumers to greatly increase consumption as unit prices decrease.

Binswanger (2000) suggests differing types of methods is responsible for a portion of the witnessed variability. Sundry other factors also influence the variation of the rebound magnitude, such as geographic location, socio-economic status, and number of vehicles at a household. Living in rural regions often generates a low fuel price elasticity and rebound because of the large number of miles already driven and limited public transportation. Conversely, dwelling in urban areas often elicits a high fuel price elasticity because of readily available alternative transportation, leading to increased rebound effects (Greene et al, 1999). Households with little disposable income generally experience low fuel price elasticity and rebound effects as well, largely because they already minimize the number of miles driven as a cost-savings measure. Households with multiple vehicles and multiple drivers often produce larger rebound effects because the most fuel efficient vehicle is driven more often to save fuel (Fronzel et al, 2012).

### *2.2.3 SURVEY-BASED STUDIES AND FINDINGS*

Surveys have been the main instrument found in literature to estimate the degree of rebound occurring for personal transportation. Fronzel et al (2012) issued surveys to a group of households for a six-week period for thirteen contiguous years in spring, in Germany between 1997 and 2009. The survey gathered information on the typical transportation behavior of each member of the household, price paid for fuel, volume of fuel consumed, and distance driven on each tank of gasoline. Also collected was general household information. Data was gathered to investigate the magnitude of the rebound effect as well as its heterogeneity across households,

and found the overall rebound to be approximately 60%. The study found no indication that factors such as affluence, geographic location, or number of cars per household differentiated the rebound effect. The study did find that the magnitude of rebound was influenced by driving intensity; households that drove many miles prior to increasing fuel efficiency exhibited less rebound than households that previously drove relatively few miles.

Greene et al. (1999) also administered surveys to estimate vehicle usage in one-, two-, three-, four-, and five-vehicle households over a 15-year period in the United States. The data was separated based on number of vehicles per household while combining all other household-level effects. They found that over the 30 years prior to their research, the average number of vehicles per household increased while the average number of people per household decreased over that same period. One-vehicle households had a 28% rebound and two-, three-, four, and five-vehicle households had 25%, 17%, 22%, and 21% rebound effects, respectively. These results hint at decreasing fuel price elasticity with increased number of vehicles owned.

Coad et al. (2009) used data from a survey that collected information on the decision-making process leading up to purchasing new fuel-efficient cars. The member of the household asked to complete the survey was the individual who either bought the last car or will buy the next car, in order to have the data pertain specifically to car buyers and not the relations thereof. The survey gathered data on Swiss households randomly sampled from a phonebook, and sought to understand whether prospective vehicle buyers were motivated by either or both of two different types of fuel economy policies: financial incentives (extrinsic) and non-financial incentives (intrinsic). They found that consumers either responded positively to one type of policy and not the other. These two policy types need not be antithetical to each other by nature, but appear to be viewed as such by consumers.

#### *2.2.4 LIFE CYCLE ASSESSMENT*

Products have multiple phases comprising their lives, generally identified as raw material acquisition, manufacturing, use, and end of life (Graedel & Allenby, 2009). Life cycle assessment is a systematic tool for determining the environmental impact of a product or process throughout its lifetime. In particular, it allows for the life cycle stages of the product or process to be identified, and potentially improved, while avoiding the shifting of burdens. The impacts in an LCA are often assessed across multiple impact categories. Owens (1997) identified the impact categories as global warming, stratospheric ozone, acidification, eutrophication, photochemical smog, ecotoxicity, habitat loss, and biodiversity.

Schafer et al (2006) found the use phase produces over 90% of the lifetime GHG emissions for conventional internal combustion engine (ICE) automobiles. Samaras and Meisterling (2008) matched this finding, stating the use phase of ICE-powered vehicles emits approximately 87% of the lifetime GHG. When comparing conventional vehicles with hybrid electric vehicles (HEVs), the production phase GHG emissions are nearly equivalent; the impact of battery production, the chief difference between conventional vehicles and HEVs, is nominal (Samaras & Meisterling, 2008). Helms et al (2010) identified the use phase to account for 75% of lifetime emissions. All the studies identified the use phase as generating the largest impact, meaning the vehicle utilization by the consumer has the greatest life cycle environmental impact. This suggests that from a sustainability perspective, the use phase and potential rebound effect are relevant.

### **2.3 MATERIALS AND METHODS**

#### *2.3.1 SURVEY ADMINISTRATION*

A consumer survey was administered to collect data pertaining to four overall categories. First, general household data was collected. This included information such as number of vehicles in household, number of drivers in household, and type of geographic region of residence (rural, suburban, or urban). Also included was a categorization of the vehicle(s) in each surveyed household: vehicle age, type, weekly miles driven, and frequency of refueling per month. The second type of data pertained to the respondent's driving habits, including annual miles driven, destination and frequency of commute, use of alternate types of transportation, at what gasoline price increase would elicit a change in driving habits, and how driving habits would change at that indicated fuel price increase. The third data category reflected the participant's motivation for purchasing another vehicle. Such data encompassed anticipated number of years until purchase, vehicle type, new or used, ranking of personal importance of vehicle attributes, a comparison of fuel economy between the current vehicle and purchased vehicle, and how their driving habits may change following the change in vehicle. The vehicle attributes that were ranked were fast acceleration, luxury amenities, brand loyalty, efficient fuel economy, "greenness", influence of others, high performance rating, high power rating, price/affordability, high reliability rating, high safety rating, large size, sporty style, cargo space, and passenger seating capacity. The fourth and final type of data collected was demographics, with similar categories to those collected by the U.S. Census Bureau for comparability. A copy of the survey instrument utilized can be found in the appendix.

The survey was produced using Qualtrics and was posted on Craigslist in order to reduce sampling bias by allowing any qualified participant to complete the survey anytime and anywhere within the target area, requiring solely an internet connection; survey responses were not limited to conventional work-day hours nor proximity to the university. A survey incentive

of a \$5 gift certificate was offered to eligible participants who completed the survey. Eligible participants were required to meet three criteria: be 18 years of age or older, own at least one vehicle, and be a resident of the Madison Metropolitan Statistical Area (MMSA). The MMSA is composed of Columbia, Dane, and Iowa Counties, respectively, in Wisconsin (Wisconsin Department of Revenue, 2014). In order to preserve the integrity of the data with respect to the desired criteria listed above, data associated with participants in breach of one or more of the eligibility criteria were rejected and not used in the analysis. One hundred ninety eight responses were collected, with 67 responses rejected on the basis of residence outside the MMSA, netting 131 respondents used in this analysis. Incomplete surveys were not included in the analysis. The survey instrument and research protocol was approved by the University of Wisconsin-Madison Institutional Review Board (IRB ID 2015-1552). The study took place over a 66-day period from mid-February to late-March 2016.

### 2.3.2 DATA ANALYSIS

To begin to analyze the survey data, correlation coefficients were calculated for the entire data set to identify statistically significant correlations within the data. R-values were calculated for a 95% confidence interval (CI). The calculations for the 95% CI can be found in the appendix. Based off tabulated values for the specific confidence interval and sample population size, r-values with absolute value greater than 0.197 were deemed statistically significant. Analysis of variance (ANOVA) calculations were completed to assess whether statistically significant differences existed between urban-residing participants and those in suburban residences. All the ANOVA calculations employed were two-factor ANOVA without replication and  $\alpha$  equaling 0.05. The parameters analyzed between the two groups were annual household miles driven, which gasoline price increase would goad a change in driving tendencies, and number of drivers

per household. The survey collected annual household miles driven data compartmentalized by mileage ranges. Consequently, to obtain discrete annual mile values from which to calculate the variance between the suburban and urban groups, the center value of each range was used in the ANOVA calculation. The annual mileage ranges were 0-5,000, 5,000-10,000, 10,000-15,000, 15,000-20,000, 20,000-35,000, 35,000-60,000, 60,000-100,000, 100,000-150,000, and greater than 150,000 with respective discrete midpoint values of 2,500, 7,500, 12,500, 17,500, 27,500, 47,500, 80,000, 125,000, and 150,000.

Of the 131 eligible, analyzed respondents, 59 lived in suburban areas, 60 lived in urban regions, and 12 lived in rural locations. To remedy the problem of unequal sample sizes for the ANOVA tests, the mean average of the values of the 59 suburban data points was used to populate the 60<sup>th</sup> suburban data point, providing equal sample sizes between the urban and suburban groups. Rural residents were not included in the ANOVA analyses due to the dearth of rural respondents.

## **2.4 RESULTS AND DISCUSSION**

### *2.4.1 HOUSEHOLD MILES TRAVELLED*

Annual household miles travelled (HMT) was compared between the suburban and urban subgroups of the survey, utilizing an ANOVA test to determine whether the groups were statistically different in a number of categories. The test produced a P-value of 0.6575, F of 0.1986, and  $F_{critical}$  of 4.0069, indicating no statically significant difference between the groups with regard to annual HMT. This result may suggest that urban-specific factors such as availability of public transit, increased practicality of walking or bicycling as a transportation method, fees and complications associated with parking, and increased traffic congestion

compared to suburban routes do not materially affect the difference in number of miles driven between the two groups.

Such a finding is interesting in part because the above-listed urban factors are touted as methods to reduce vehicle miles driven in cities, supposedly reducing the number of vehicles on the roadways and their associated emissions. However, the findings in this analysis hint that urban groups may not reduce their miles driven as was anticipated. It is important to note that this metric was calculated on a household basis, not per individual. An ANOVA test addressing the number of drivers per household in each group produced a P-value of 0.0009, F of 12.2425, and  $F_{\text{critical}}$  of 4.0040, implicating a significant difference in the number of drivers per household between the groups, with the suburban group boasting a higher number of drivers per household. The lack of differentiation between annual household miles travelled may be an artifact of the different number of drivers per household between groups.

When considering that suburban households included more drivers than did urban households and that each household drove approximately the same number of miles, it can be estimated that the miles travelled per driver was *less* for the suburban group compared with the urban group. This trend appears to dispute the idea that urban residents drive fewer miles due to the urban factors discussed above, and that, furthermore, there could be promising potential to expand urban public transportation systems to further reduce the number of miles driven by personal vehicles. The current forms of alternate transportation in Madison, Wisconsin, are a developed Metro bus system, expansive bike lanes, and sidewalks for pedestrians. Larger cities may boast a subway or rail system in addition to bus, bike, and walking options. The absence of a rail system in Madison may have influenced the findings from the survey, as rail is an effective method for moving large numbers of people.

#### *2.4.2 ANTICIPATED CHANGE IN DRIVING HABITS DUE TO CHANGES IN FUEL COST*

The magnitude of fuel price increase that would incite a change in driving habits between the two groups was then compared using an ANOVA test. The result yielded a P-value of 0.2952, F of 1.1153, and  $F_{\text{critical}}$  of 4.0040. Figure 1 shows the different fuel price increases and the distribution of the participants' responses. This result implicates there is no statistical difference between the groups with respect to the fuel price jump that would cause a change in driving habit. Consumer change in driving tendencies due to increases in fuel price is a function of the cost of use of the vehicle. A parallel perspective of this result is that there is no bona-fide difference in fuel price elasticity between the two studied groups. This finding may be surprising; when compared to suburban areas, urban regions have more options of readily-accessible alternate modes of transportation to adopt when fuel prices rise. Consequently, this dynamic may entice one to posit that the urban group would change their driving habits at a smaller increase in fuel price than the suburban group, creating a higher fuel price elasticity for the urban group. The findings, however, suggest this is not the case. Rather, it is seen that the urban-specific factors discussed in section 2.4.1 have no net increase in fuel price elasticity.

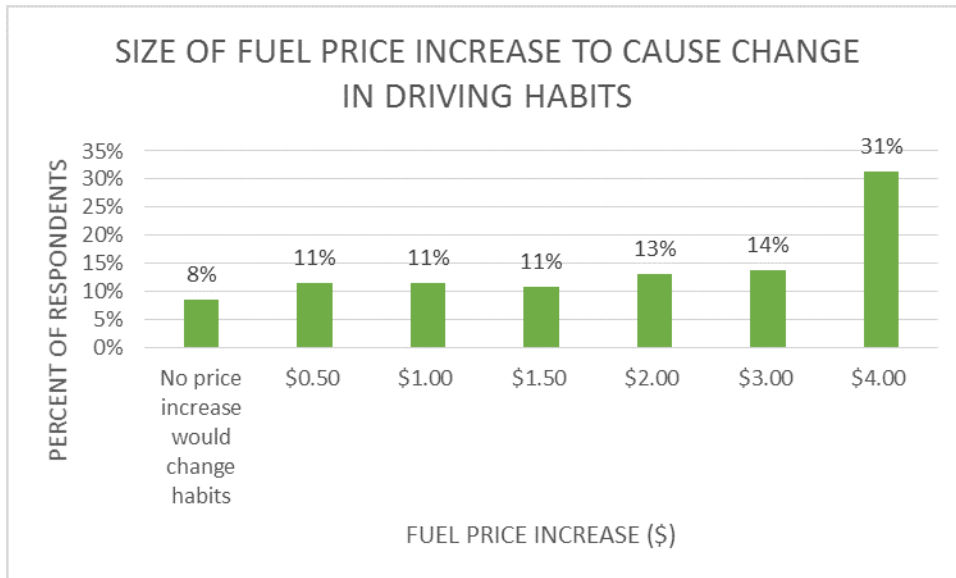


FIGURE 1. FUEL PRICE INCREASE TO CAUSE CHANGE IN DRIVING HABITS.

Figure 1 compares behavioral responses at the specified fuel price increase among the suburban group, the urban group, and the total survey population—the rural group was included in the total percentage in Figure 1 but was not separated out due to its prohibitively small sample size. To determine this specified fuel price, the survey directly asked the participants to identify which size of price increase would cause them to alter their driving tendencies. Thus, the fuel price increase alluded to varies between participants, and it is the behavioral response to that price change that is being analyzed here. Figure 2 plots the daily average fuel price during the study from which the increase in price is based (GasBuddy.com, 2016). It can be observed in Figure 3 that a larger percentage of the suburban group compared to the urban group would reportedly not change their driving habits in response to their specified fuel price increase. It is tempting to explain this by the relative lack of alternate methods of transportation available to the suburban group, making it more difficult for that group to adopt different driving habits in the face of increased fuel prices. Conversely, the urban group can more readily utilize bus, bike, or walking routes, respectively, to combat rising prices at the pump. This propensity to consume alternate

modes of transportation is supported in Figure 3, where an eight percentage point spread between the two groups is displayed. Furthermore, the higher population density experienced by the urban group may increase the likelihood of individuals finding a carpooling circle, though both groups polled as nearly equal in their desire to carpool more often. The percentages in Figure 3 do not add up to 100% because the behavior changes are not mutually exclusive; one may increase consumption of public transit while also increasing carpooling activity. Table 1 shows the current and anticipated carpooling rates for the total surveyed population and the two groups. Further research would be required to more robustly demonstrate the dominating factors underlying these trends.

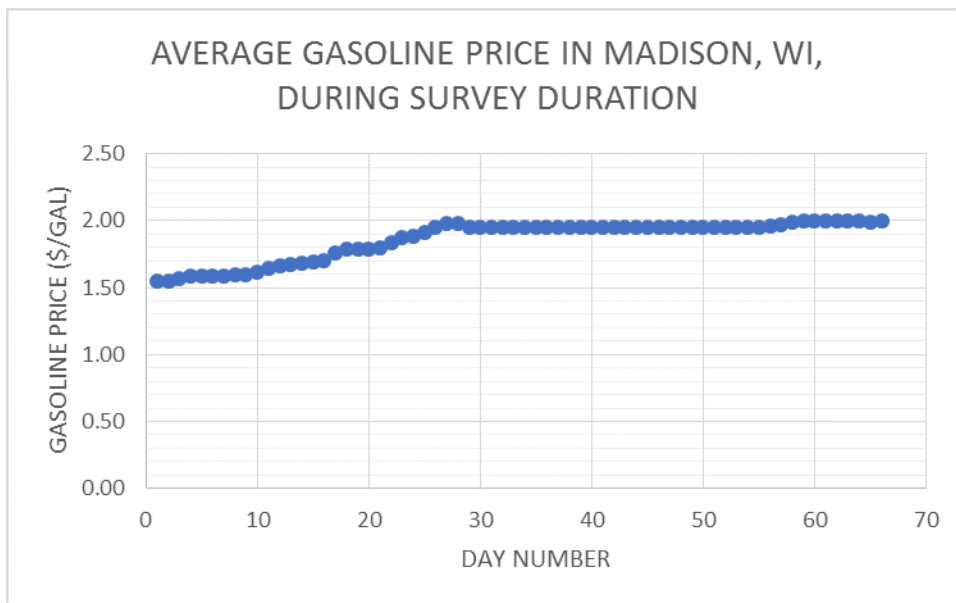


FIGURE 2. AVERAGE GASOLINE PRICE IN MADISON, WI, DURING SURVEY DURATION.

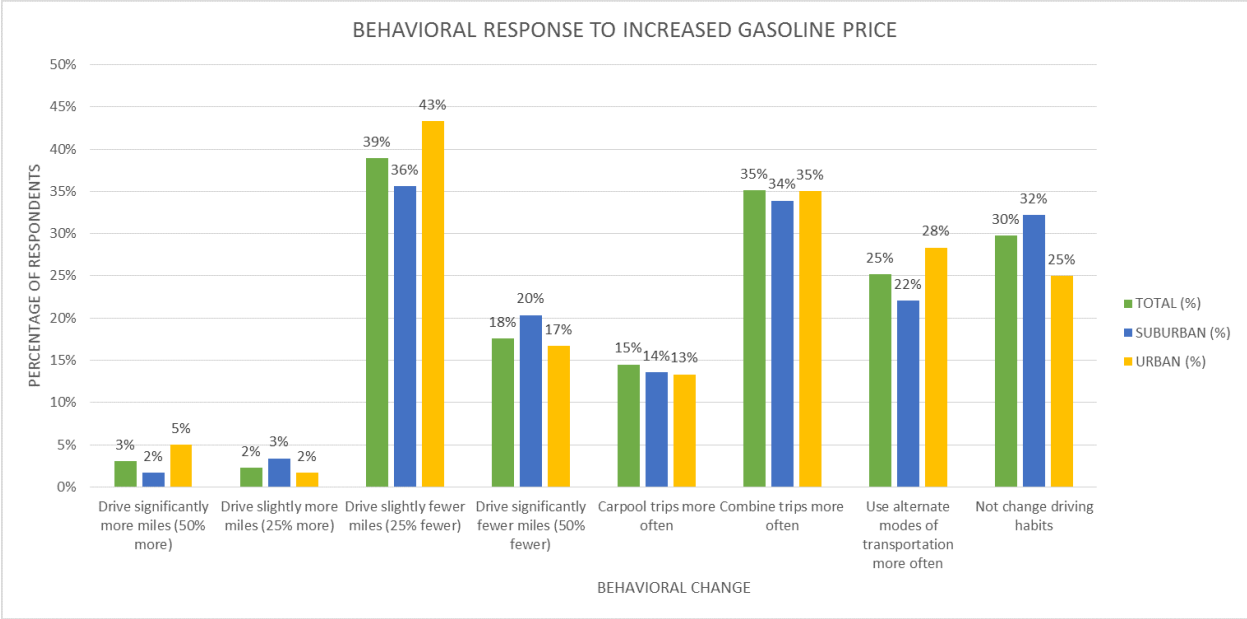


FIGURE 3. BEHAVIORAL RESPONSE TO INCREASED GASOLINE PRICE.

TABLE 1. CURRENT AND ANTICIPATED CARPOOL RATES AT IDENTIFIED FUEL PRICE INCREASE.

	Total	Suburban	Urban
<b>% currently carpooling</b>	14.5%	6.1%	6.1%
<b>% that would increase carpooling</b>	14.5%	6.1%	6.1%
<b>% currently carpooling and would increase carpooling</b>	7.6%	2.3%	3.8%
<b>% not currently carpooling and would increase carpooling</b>	6.9%	3.8%	2.3%

It would be logical to hypothesize that an increase in the price of gasoline would influence the destinations to which drivers decide to commute, often based on the driver’s personal perception of each destination falling into the “need” category or “want” category. In this study, the need category was comprised of trips to work, school, place of worship, and grocery shopping, while the want category contained entertainment, other shopping (i.e. for pleasure or entertainment, not errands), visiting family/friends, and non-shopping errands. Table 2 shows the percent of respondents in each group who travel to each of the eight destination categories (work, school, grocery shopping, other shopping, well-being, family/friends, non-shopping errands, and entertainment) and at which frequency. “Well-being” includes destinations such as the gym,

place of worship, medical appointments, *etcetera*, and “Non-Shopping Errands” encompass [non-medical] appointments, meetings, *etcetera*. An interesting observation from Table 2 is that a larger percentage of the suburban group generally commuted to their destinations at a higher frequency (multiple times per week) compared to the percentage of the urban group that exhibited this behavior. Additionally, a larger percentage of the urban group compared to the percentage of the suburban group travelled to the destinations at a lower frequency (less than five times per month). A potential explanation for this behavior could be that the urban group used other methods of transportation to a larger extent than did the suburban group to travel to the specified destinations. Increased consumption of alternate transportation may reduce the number of occurrences a participant drove his/her personal vehicle to the destination, which would be consistent with the data. Such an explanation, however, is solely a hypothesis and would require additional research to validate the mechanisms determining this difference in behavior.

**TABLE 2. EIGHT CATEGORIES OF TRAVEL DESTINATIONS AND RESPECTIVE TRAVEL FREQUENCIES.**

	Work		School		Grocery Shopping		Well-Being	
Frequency	Suburban	Urban	Suburban	Urban	Suburban	Urban	Suburban	Urban
5+ times per week	76%	50%	14%	7%	2%	0%	5%	2%
1-4 times per week	15%	20%	7%	2%	19%	15%	17%	15%
1 time per week	7%	3%	3%	5%	15%	18%	10%	2%
1-4 times per month	10%	5%	2%	3%	8%	15%	17%	10%
<1 time per month	3%	13%	0%	3%	0%	8%	7%	28%
	Other Shopping		To Friends/Family		Non-Shopping Errands		Entertainment	
Frequency	Suburban	Urban	Suburban	Urban	Suburban	Urban	Suburban	Urban
5+ times per week	3%	5%	2%	0%	7%	3%	8%	2%
1-4 times per week	20%	18%	17%	8%	10%	3%	36%	30%
1 time per week	15%	25%	5%	12%	2%	5%	19%	22%
1-4 times per month	14%	33%	25%	23%	14%	12%	68%	75%
<1 time per month	10%	12%	8%	32%	17%	15%	56%	82%

Economically-speaking, increasing the efficiency of a good is synonymous with decreasing the price of that good. For vehicles, increasing fuel efficiency is equivalent to decreasing the cost of use and thus the cost of ownership. As discussed in section 2.2.1, this can create a rebound effect, where consumers increase their consumption of the good. Figure 4 plots the expected driving habit change in response to the adoption of a more fuel efficient vehicle across both groups (urban and suburban) as well as the total surveyed population—the data for rural participants was included in the total but was not presented separately due to its impedingly small sample size. It can be seen that all three data sets followed the same trend: a very small subset reported they would drastically increase their number of miles driven, a small but slightly larger portion anticipated a slight increase, and the largest portion of respondents who planned

on purchasing another vehicle did not foretell any increase in their driving behavior. A curiosity intrinsic to the self-reported, conjectural nature of the data is whether the respondents accurately anticipated their future behavior. Hypothetically predicting what one might do and what one does in reality are not always consistent with each other. It may be realistic to think that some participants—namely under the *no change* umbrella—did not recognize all the minute ways they may marginally increase their number of miles driven, such as taking the sporadic road trip, combining trips less often, or volunteering to drive more frequently when travelling with a group. For the purpose of this analysis, however, the participants’ responses were assumed to be fully accurate.

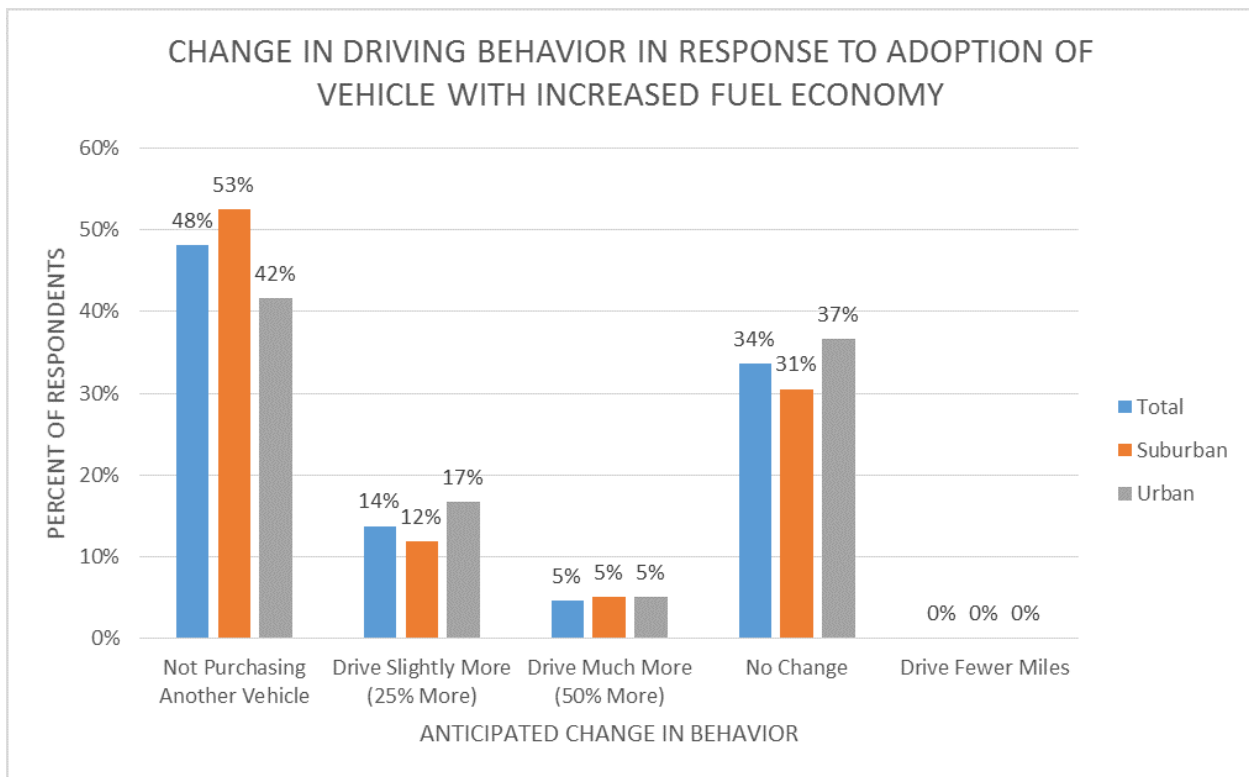


FIGURE 4. CHANGE IN DRIVING BEHAVIOR IN RESPONSE TO ADOPTION OF VEHICLE WITH INCREASED FUEL ECONOMY.

With respect to the potential for the rebound effect to occur, 19% of survey respondents indicated that they would expect to drive more after the adoption of a new fuel efficient vehicle.

Only 5% indicated that they would drive 50% more miles than they currently do, while 14% indicated they would drive 25% more miles than they currently do. This suggests that on a household level, there is significant potential for the rebound effect to occur with approximately a fifth of the respondents surveyed. Although this may not result in backfire, it will decrease the anticipated fuel savings due to the adoption of a more fuel efficient vehicle. Coexistent with the decrease in anticipated fuel savings is a decrease in the anticipated emission reduction associated with adoption of fuel efficient vehicles. Based on the current number of annual vehicle miles driven by the respondents and the anticipated percent increases, this would result in an increase of 208,000 vehicle miles traveled by the survey population, or a 9% increase, which would impart an increase in energy used. Table 3 presents household and consumer characteristics that were found to be significantly correlated with a propensity to increase miles driven when adopting a more fuel efficient vehicle. It can be interpreted that households with a larger number of drivers are less likely to exhibit a rebound. Additionally, consumers who frequently use alternate methods of transportation, including the bus system and carpooling, have a significant likelihood of exhibiting a rebound when adopting a fuel efficient vehicle. This suggests that consumers of alternate modes of transportation may do so, at least in part, because they want to reduce their fuel consumption, whether it be for financial or environmental reasons.

**TABLE 3. STATISTICALLY SIGNIFICANT CORRELATION COEFFICIENTS LIKELY ASSOCIATED WITH FUEL EFFICIENT VEHICLE ADOPTION.**

	<b>Increase miles driven with adoption of fuel efficient vehicle</b>
<b>Number of drivers in household</b>	-0.2528
<b>Frequent use of alternate transportation</b>	0.2373
<b>Currently uses bus system</b>	0.2193
<b>Currently carpools</b>	0.2764

### *2.4.3 CONSUMER VALUATION OF VEHICLE ATTRIBUTES*

Figure 5 depicts the percent of participants who ranked each attribute 1<sup>st</sup>, 2<sup>nd</sup>, 3<sup>rd</sup>, *etcetera*, where a ranking of 1<sup>st</sup> corresponds to most important and 15<sup>th</sup> is least important to that participant. The size of each area in the graph is proportional to the percent of respondents it represents. No individual attribute received a majority as most important—or at any other ranking. Affordability received a plurality of 24% of respondents valuing it as most important, and fuel economy came next as most important to 17% of participants. One thing that should be readily observable from the figure is that consumers of personal vehicles are very heterogeneous; their preference of what is desired in a vehicle varies widely among individuals. In other words, an attribute highly valued by one consumer may be an attribute little valued by another.

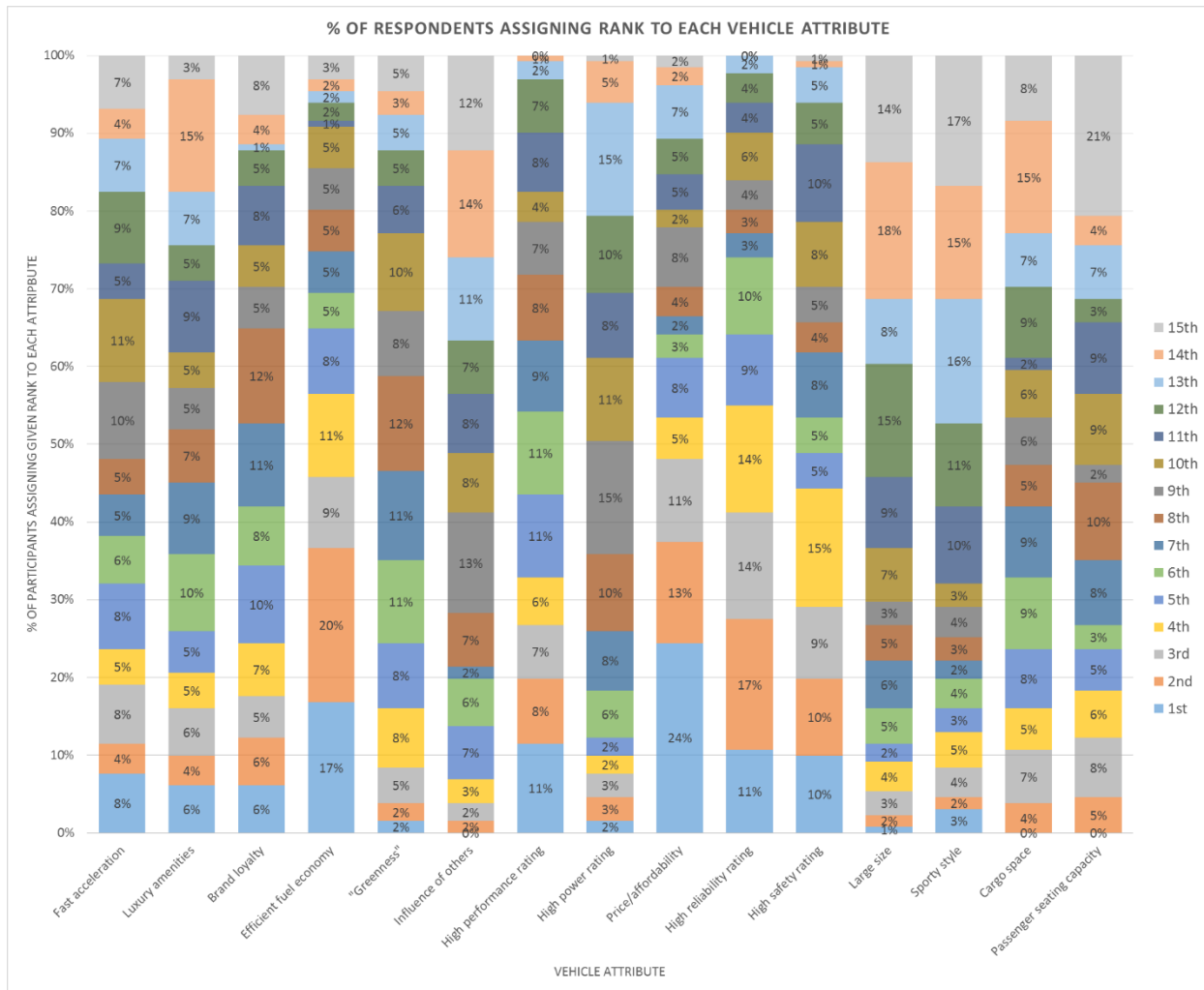


FIGURE 5. PARTICIPANTS' RANKING OF IMPORTANCE OF VEHICLE ATTRIBUTES.

The findings pertaining to participants' rankings of vehicle attributes are important for understanding consumer tastes and preferences in vehicle selection. It is important to understand that the consumer-base is composed of sundry individuals who possess many different opinions on which vehicle attributes are most valuable. This information may be used to promote fuel efficient vehicles to the largest possible portion of the population by combining efficient fuel economy with other highly-prized vehicle attributes to increase the appeal of fuel efficiency to the largest portion of the driving population. Figure 6 presents the percent of participants who

ranked each attribute as most important. It can be seen that the top five attributes—price/affordability, efficient fuel economy, high reliability rating, high performance rating, and high safety rating—comprise 73% of all participants. This may be used, in conjunction with the vast body of research pertaining to consumer purchasing behavior, to indicate which attributes can be coupled with efficient fuel economy to appeal to the widest range of consumers. If fuel efficiency was combined with the other desired attributes, consumers who adopt a vehicle for features other than fuel economy also derive the benefit of efficient fuel use. This benefit of combining fuel economy with other attributes becomes increasingly apparent when combining subsequent attributes.

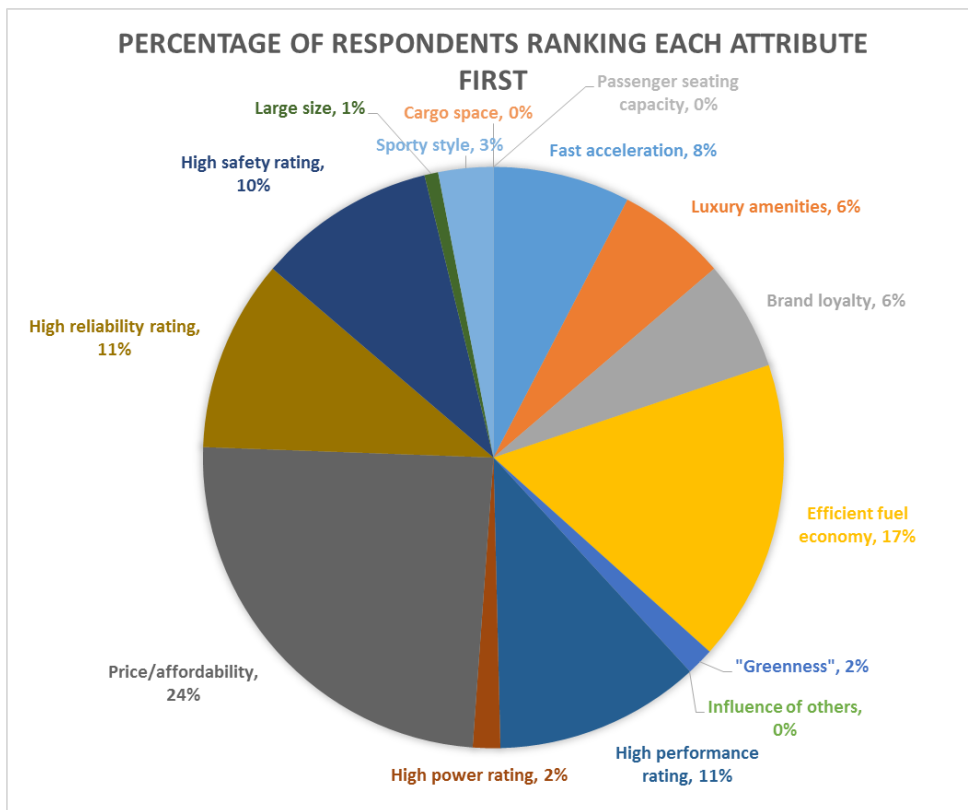


FIGURE 6. PERCENTAGE OF RESPONDENTS RANKING EACH ATTRIBUTE AS MOST IMPORTANT.

Table 4 expresses groups of participants defined by their most highly ranked attribute and shows only the notable groups that had eight or more participants; smaller groups were not large enough to produce any aggregate behavioral trends and were not included in the table. The table shows a view beyond solely the first ranked attribute for each participant and displays additional automobile attributes that are either highly valued or least valued across the members of each group. In the table, highly important was defined by a mean average of an attribute ranking between 1st-ranked and 5th-ranked, least important was defined by a mean average of an attribute ranking between 11th-ranked and 15th-ranked, and attributes not listed under most important or least important had mean average attribute ranking between 6th-ranked and 10th-ranked and were termed moderately important. The numerical ranking scale defines 1st as most important and 15th as least important. The group size is the number of participants who ranked the specified attribute as most important (1st-ranked). Only groups with eight or more respondents were included in this table. The information in this table can be applied in the same manner as the data in Figure 5 and Figure 6 to help suggest which automobile attributes to aggregate with fuel efficiency. It can be observed that participants who most highly rated fuel economy also highly valued affordability and reliability, indicating these attributes may be good candidates to be aggregated.

**TABLE 4. SELECTED GROUPS THAT RANKED THE SPECIFIED VEHICLE ATTRIBUTES AS MOST IMPORTANT AND LEAST IMPORTANT**

<b>Group by Most Important Attribute</b>	<b>Group Size</b>	<b>% of Total Respondents</b>	<b>Highly Important</b>	<b>Least Important</b>
Fuel Efficiency	22	17%	Price/affordability High reliability rating	Influence of others Large size Sporty style
Vehicle Price/Affordability	32	24%	Efficient fuel economy High reliability rating	Luxury amenities High power rating Large size Sporty style
Fast Acceleration	10	8%	Luxury amenities	Large size Cargo space
Luxury Amenities	8	6%	Brand loyalty High performance rating	Large size Cargo space

Additionally, this data can be used to estimate the portion of the surveyed population to whom the rebound effect applies most: those who have a propensity to adopt a fuel efficient vehicle and consequently rate fuel efficiency as a highly important attribute. This faction is approximately 65% of the sample population. Focus should be placed on this portion of drivers to study, understand, and ultimately mitigate the rebound effect. The remaining 35% of the population may likely be increasingly less expected to adopt a fuel efficient vehicle, not making them good contenders for displaying a rebound through their non-adoption.

#### *2.4.4 DEMOGRAPHICS*

Figures 7-10 show distributions for each demographic category for the surveyed population and the MMSA. The surveyed population is generally representative of the general population, with some exceptions. Notably, slightly over a quarter of respondents were Hispanic, which is much larger than the 5% of the overall population. The age distribution was loosely centered around 20-50 years old with few participants occupying the extremities for the survey, whereas the MMSA populations is more evenly distributed. This is likely due on the younger end to the 18 years or older age constraint for the survey, and on the older end, older individuals may be less prone to participate in an internet-based study. The comparison between household incomes was similar, with the surveyed population slightly more centered on middle to middle-upper incomes. Education level was higher for the surveyed population, but was not entirely dissimilar to that of the general population. Race, gender, living situation, and marital status were similar between the two populations. A table of the comprehensive demographic data is available in the appendix.

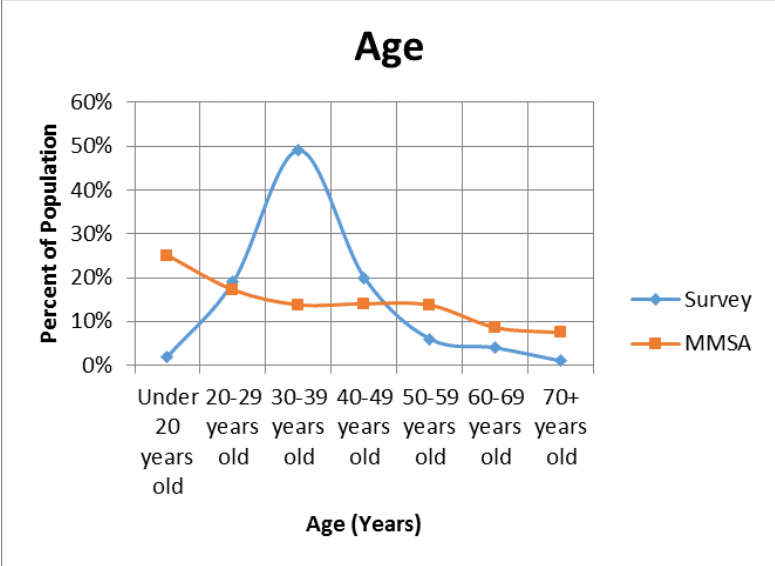


FIGURE 7. AGE DISTRIBUTION FOR SURVEYED POPULATION AND MMSA.

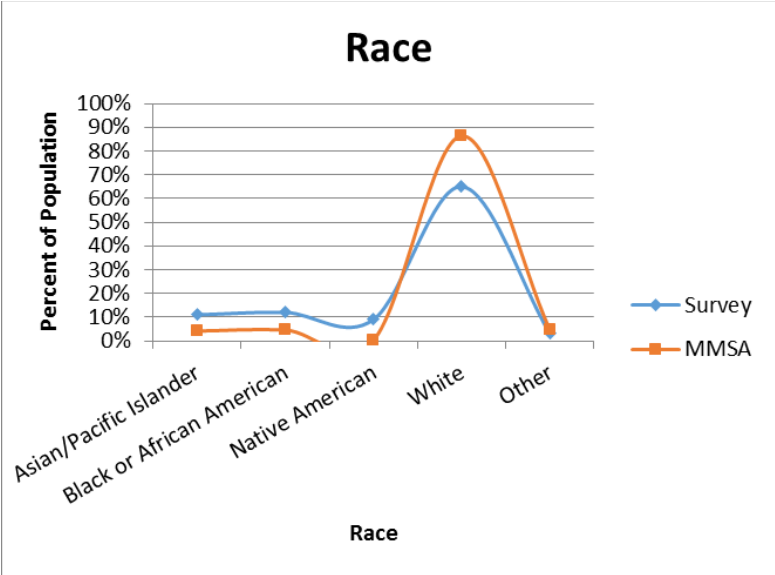


FIGURE 8. RACE DISTRIBUTION FOR SURVEYED POPULATION AND MMSA.

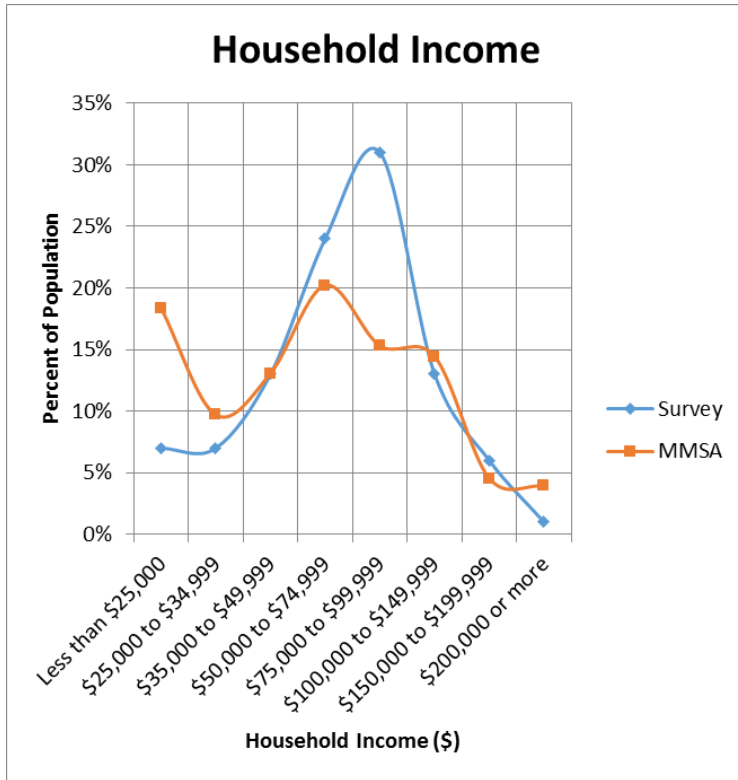


FIGURE 9. HOUSEHOLD INCOME DISTRIBUTION FOR SURVEYED POPULATION AND MMSA.

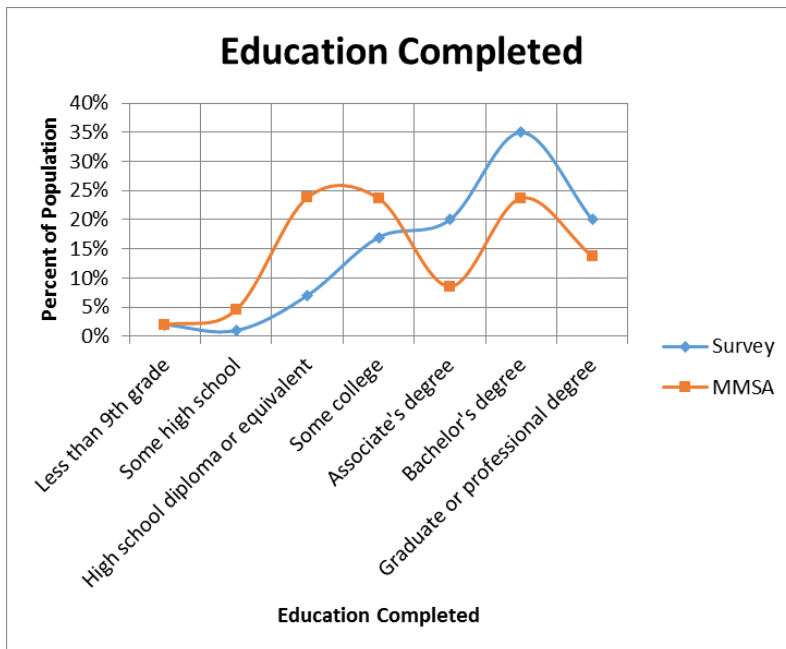


FIGURE 10. EDUCATION COMPLETED DISTRIBUTION FOR SURVEYED POPULATION AND MMSA.

## 2.5 CONCLUSIONS

### *2.5.1 CONCLUSIONS*

The rebound effect warrants consideration when working to reduce the level of fuel consumption and environmental impact of vehicle transportation. The rebound effect pertaining to vehicle fuel consumption explains the increase in miles driven associated with improvements in fuel economy. This study analyzed survey data to glean insight into how consumer driving habits change as the price of fuel changes, either via changes in gasoline price at the pump or through changes in vehicle fuel efficiency. An analysis was completed between urban and suburban residents, and the results were used to attempt to explain the factors influencing the differences between the two groups.

It was found that there was no significant difference between the two groups for the size of fuel price increase that would cause a change in driving habits. The anticipated change in driving habits did vary, however, between the two groups. The urban groups signified an increase in consumption of alternate methods of transportation in the face of increasing fuel prices compared to the suburban group. This may be explained by alternate transportation being more available in urban areas than in suburban locations. Interestingly, it was found that drivers in urban locations may drive more miles than drivers in suburban places. Of the entire survey population, 19% of respondents indicated they would increase their number of miles driven upon adoption of a more fuel efficient vehicle. Five percent specified they would drive significantly more (50% more miles), while 14% determined they would drive slightly more (25% more miles). This behavior would lead to a 9% increase in miles driven, equating to 208,000 additional miles.

This study also investigated consumer preferences and motivations when purchasing a vehicle. By collecting rankings of the extent to which participants value certain vehicle attributes, it was

observed that automobile drivers are heterogeneous in their valuation of vehicle attributes, where no single attribute donned a majority of participants ranking it as most important. This diverse makeup of vehicle drivers can be used to promote widespread adoption of fuel efficient vehicles by aggregating efficient fuel economy with other highly-valued attributes into a single vehicle. This could aid the adoption of fuel efficient automobiles by consumers who do not necessarily value fuel efficiency, but rather value the other attributes, and attain fuel economy as a derivative of pursuing the other targeted, aggregated features. It can also be used to help identify the portion of drivers who are more likely to exhibit a rebound and those who are not based on the drivers' propensity to purchase a fuel efficient vehicle. This sub-group is heterogeneous itself with regards to valuation of other attributes despite sharing the preference for fuel efficiency.

### *2.5.2 LIMITATIONS*

As with all studies, this research encountered certain limitations. The short duration of the study imposed a practical limit on the population size of the survey. A longer study duration and larger sample size may have uncovered additional results that either illustrate new trends or explain results that were currently found. Another limitation endured in this study was that the data was entirely self-reported, thus subject to potential intentional or unintentional inaccuracies. This could be mitigated, in part, by implementing methods to collect numerical driving data for each participant, such as a GPS chip or other tracking device. This option is amply less practical for logistical and privacy reasons. Another source of inaccuracy was the ability of the participants to correctly anticipate how they would react to a hypothetical future scenario. This suffers from the disparity of what people ideologically think they would do and what they would actually do in reality. A driving data collection chip would not remedy this source of inaccuracy.

### *2.5.3 FUTURE STUDIES*

With findings and answers comes divers more questions and inquiries. One such ensuing question arisen in this research was how rural households would compare to the urban and suburban groups. The drastically different settings between rural establishments and urban metropolises may lead to many interesting results. Future studies would benefit from generating a large sample size that includes sufficient number of participants in rural locations along with urban and suburban settings. Such a study could be valuable and applicable, considering the material faction of the national—and global population—that live in rural abodes.

Analyzing different locations, not just the MMSA, is additional fodder for additional future studies. This could include similar research to be done on other cities or towns as well as increasing the scale of the study from the city level to state-wide level and ultimately the national level. The potential for what may be found in such research is stimulating. One could make comparisons among states by geographical region, chief economic industry of the state, or numerous other factors. Similarly, assessments among different nations could generate valuable results. By vastly expanding the geographical scope of this type of research, a comprehensive understanding of vehicle consumers and drivers can be assembled, which may ultimately be a strong tool in the toolbox required reduce the environmental impact of modern transportation.

### ***3.0 FUEL EFFICIENT VEHICLES AND THE REBOUND EFFECT: THE ENVIRONMENTAL IMPACT OF EFFICIENCY***

The following chapter is a reproduction of an article in preparation for submission to Transportation Research Part D, with the citation:

Mahoney, J; Hicks, A. 2016, *Fuel Efficient Vehicles and the Rebound Effect: the Environmental Impact of Efficiency*

This article appears as prepared for submission, although style and formatting modifications have been made.

### 3.1 INTRODUCTION

Concerns over environmental quality and the changing climate have become increasingly prevalent in modern society (Gadenne et al, 2009). Legislation has been passed to preserve natural resources (Freeman & Dougherty, 2015), while consumer preferences for sustainable goods—*green* designs—has helped shift product design towards reducing negative impacts on the environment (Medeiros et al, 2014). Consumers are now offered scores of *eco-friendly* products and services, from household products and food supply to lawn care and laundering services. Among the many market sectors experiencing rapid growth in green products is the automobile industry, where vehicles have become increasingly more fuel efficient through incorporation of innovative technologies to improve fuel efficiency (U.S. Department of Energy, 2015).

The chief goal of improving vehicle fuel efficiency is to reduce the amount of fuel used by the transportation sector, ultimately reducing the amount of greenhouse gases (GHGs) and other tailpipe air pollutants emitted (Karplus et al, 2013). Current estimates indicate the transportation sector emits approximately a quarter of all anthropogenic GHG emissions (Archer, 2012), with passenger automobiles comprising the majority of these emissions (Maclean & Lave, 2003). The primary strategy in the United States to reduce fuel consumption is legislation to improve vehicle fuel efficiency through technological advancements (McConnell, 2013). The Corporate Average Fuel Economy (CAFE) standards are the main U.S. regulatory structure that mandates fuel economy standards for vehicle fleets and allows for fiscal retribution against manufacturers not in compliance (Austin & Dinan, 2005). A new set of fuel economy standards passed in 2011 requires model years 2017 to 2025 to improve fuel efficiency by five-percent annually for

passenger cars and similar mandates for light trucks of the same model years (Karplus et al, 2013).

It is relevant to consider the different stages of a product's life and their respective environmental impacts to determine how to best reduce the overall impact. A product's life can be delineated into life cycle phases, traditionally identified as raw material acquisition, manufacturing, use, and end of life (Graedel & Allenby, 2009). A life cycle assessment is a systematic tool commonly used to identify the lifetime environmental impact of a product or service and can identify the various environmental impacts associated with each phase across multiple impact categories to reveal which stage generates the largest impact. This can then help identify which stages have the largest potential to most effectively reduce the impact while avoiding shifting the environmental burden from one stage to another. Prior studies of lifetime GHG emissions for conventional internal combustion engine vehicles and hybrid electric vehicles determined approximately 90% of the emissions were produced in the use phase, where the use phase is on road usage and maintenance of the vehicle (Schafer et al, 2006; Samaras & Meisterling, 2008). This dictates that the largest life cycle impact is generated during consumer usage of automobiles. From a sustainability and impact mitigation standpoint, it stands to reason that placing emphasis on the use phase could be most effective.

When assessing the impact of efficiency changes, it is relevant to consider a phenomenon called the rebound effect, an idea which was first conceived in 19<sup>th</sup> century Britain. Economist William Jevons first theorized the rebound effect in 1865, where he observed that efficiency improvements in coal combustion in London led to an increase in consumption rather than a decrease (Jevons, 1866). The definition of the rebound effect used in this research reflects that which was outlined in de Haan et al (2005). De Haan et al (2005) presented the rebound as an

increase in demand for a product or service due to a decrease in price of that product or service through increased efficiency.

The rebound is conventionally represented as a percentage, where a value less than 100% corresponds to an overall savings, 100% exhibits no net savings, and greater than 100% relates to a net increase in consumption—known as backfire (Polimeni et al, 2008). The importance of quantifying the vehicle fuel efficiency rebound can be realized in the context of assessing the effectiveness of fuel efficiency standards as the predominant tool to reduce automotive fuel consumption, and thus reduce the corresponding environmental impact of vehicle usage. Frondel et al (2012) presented the idea that a large rebound may suggest a failure of policies that require more fuel efficient standards to meet their aim (of reducing fuel consumptions and tailpipe emissions) because of the large ensuing increase in consumption. On the other hand, the study suggested a small rebound may indicate such standards could successfully reduce fuel consumption and emissions. A survey of the literature yields a rebound range of generally 5%-65% with a central value around 20%, while Dahmus (2014) presented a value of 1000% (Greene et al, 1999; Greening et al, 2000; Saunders, 2000; Saunders, 2013; Binswanger, 2001; Frondel et al, 2012; Gillingham et al, 2013; Hymel and Small, 2015; Clerides & Zachariadis, 2008; Dahmus, 2014). The observed variability in rebound estimates may be due to different calculation methods. An implication of the majority of these values is that efforts to improve efficiency have led to a reduction in fuel consumption and energy savings, albeit accompanied with various levels of increases in miles driven.

One of the large concerns surrounding vehicle emissions is air pollution and its pernicious effects on human health. Air pollution can exacerbate health ailments afflicting the respiratory, cardiovascular, digestive, nervous, and reproductive systems, respectively, while also increasing

the incidence of cancer (Kampa & Castanas, 2008). The World Health Organization (WHO) estimated outdoor (ambient) air pollution caused 3.7 million premature deaths in 2012 (WHO, 2014), with vehicle emissions being the dominant source of ambient air pollution in many areas (Zhang & Batterman, 2013). Air pollution is one set of impact categories with which to assess the environmental impact of transportation. The WHO suggested improvements in transportation energy efficiency to improve ambient air quality (WHO, 2014). As was identified above, understanding the extent to which the rebound may be exhibited is an important consideration when attempting to achieve reductions through improvements in efficiency. A realized reduction in air pollution directly corresponds to a decrease in use phase environmental impact. This highlights the importance of understanding consumers' propensity to exhibit a rebound, and this study will present and discuss calculations for environmental impacts of the vehicle use phase along with multiple permutations of the rebound, applying the methodology to fuel consumption and eight different pollutants as impact categories. The calculations will be carried out for a surveyed population in addition to National Household Transportation Survey data sets for Wisconsin and the Milwaukee Metropolitan Statistical Area. The research motivation driving this study is a quantification of the rebound on a state-wide scale and two metropolitan statistical areas for the total populations along with rural and urban/suburban groups. Additionally, changes in use phase impacts will be calculated to investigate whether improvements in efficiency yield a net reduction in such impacts.

## **3.2 METHODS AND MATERIALS**

### *3.2.1 SURVEY INSTRUMENT*

A consumer survey was administered to investigate respondents' transportation behavior. The survey collected data pertaining to generic household information, vehicle(s) in each household,

respondents' driving tendencies and habits, participants' vehicle purchasing impetus and preferences, and demographics. A copy of the survey instrument that was utilized can be found in the appendix, along with additional methodology details and the aggregate survey data. A total of 131 respondents were used in this analysis, all of which resided in the Madison Metropolitan Statistical Area. The duration of the study was 66 days from mid-February to late-March 2016. All data was collected on a per-person or per-household basis.

### *3.2.2 VEHICLE FUEL EFFICIENCY STANDARDIZATION*

With the anticipation of using miles driven data to determine the amount of fuel consumed and pollutants emitted, it was necessary to establish standardized fuel efficiency values for each vehicle type and model year. This was accomplished by utilizing a U.S. Department of Energy (DOE) database that contained mile per gallon (mpg) fuel efficiency data for all vehicles from year 1990 to the present (DOE, 2016). Filters were set to analyze only vehicles that burned gasoline for each vehicle type and year range. Gasoline-burning vehicles were selected for because this technology comprises a strong majority of personal vehicles on the road; 82% of all new 2016 light-duty vehicle sales used only gasoline—which does not include hybrid-electric vehicles—and is an increasing portion for past years. This implicates an increasing portion of vehicles combust gasoline as the fuel source for older vehicle model years (U.S. Energy Information Administration, 2016).

This study used combined fuel economy only and did not include any calculations exclusively using city or highway fuel economy ratings. The model year range bins were 2015-2016, 2014-2010, 2009-2005, 2004-2000, 1999-1990, 1989-1980, and <1980, which reflected the ranges in the survey. To account for the DOE database truncating at model year 1990, all prior model year

bins (1999-1990, 1989-1980, and <1980) used the 1999-1990 standardized mpg value for each particular vehicle type. Calculation of the standardized mpg values was accomplished by averaging the data points for up to approximately 180 vehicles within the filtered DOE database, described by Equation 1.

$$e_z = \frac{1}{n} \cdot \sum_{j=1}^n \beta_z \quad (1)$$

The standardized fuel efficiency value for vehicle type  $z$  is  $e_z$ ,  $n$  is the number of vehicles assessed from the DOE database, and  $\beta_z$  is the combined fuel economy of vehicle  $z$ . The selection of vehicles was randomized to generate a representative sample and accurately represented the entire list in the database. The standardized efficiency values can be seen in Table 5, where NA indicates no data available in the DOE database, PUT denotes pickup truck, any hybrid vehicles of model years with NA were assigned the standardized value closest available year, and coupe indicates a two-door car and sedan indicates a four-door car (DOE, 2016).

**TABLE 5. STANDARDIZED FUEL EFFICIENCY VALUES.**

		Vehicle Type							
		Large PUT (mpg)	Small PUT (mpg)	SUV (mpg)	Hybrid SUV (mpg)	Large Sedan (mpg)	Small Sedan (mpg)	Hybrid Sedan (mpg)	Coupe (mpg)
Model Year	<1980	15.0	20.0	16.6	NA	18.8	22.7	NA	19.8
	1980-1989	15.0	20.0	16.6	NA	18.8	22.7	NA	19.8
	1990-1999	15.0	20.0	16.6	NA	18.8	22.7	NA	19.8
	2000-2004	15.1	19.7	16.0	NA	19.4	24.4	46.0	23.6
	2005-2009	15.3	19.1	17.1	26.2	19.3	23.5	40.0	22.1
	2010-2014	15.4	20.0	19.9	25.3	20.2	26.4	38.7	24.6
	2015-2016	17.2	21.4	21.0	28.8	21.1	26.8	39.3	23.0

### 3.2.3 IMPACT CALCULATIONS

This study was interested in the use phase of personal automobiles as it pertains to fuel consumption, which encompasses fuel production and distribution along with vehicle operation (fuel combustion). Argonne National Laboratory's *Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation* (GREET) 2015 model was the LCA tool employed, which is a robust database that offers expansive data on energy and emissions for fuel and transportation systems. The calculations for this study were split up into two sections: well to pump (WTP) impacts of gasoline and *operation only* data from the well to wheel (WTW) set. WTP impacts are those generated solely by the fuel cycle, which includes procurement of the raw fossil fuel, refinement and processing, and distribution and does not include consumer combustion of the fuel. WTW impacts encompass all WTP impacts as well as the impacts engendered by burning the fuel (gasoline) while driving a vehicle (operation only impacts). In this study, operation only impacts are synonymous with impacts from the combustion of the fuel since WTW and operation only impacts were determined with respect to fuel gasoline only, which would not include other operation activities such as maintenance, fluid leakage, and tire wear. Operation only was extracted to assure impacts associated with the fuel cycle were not double counted. The two impact sections—WTP and operation only—were summed to obtain a total impact estimate.

Although the GREET model utilized a myriad of impact categories, this study extracted only the following resource use and pollutant impacts: total energy [MJ], total water [ $m^3$ ], volatile organic compounds (VOCs), carbon monoxide (CO), nitrogen oxides ( $NO_x$ ), particulate matter (PM<sub>2.5</sub>), sulfur oxides ( $SO_x$ ), methane ( $CH_4$ ), carbon dioxide ( $CO_2$ ), and nitrous oxide ( $N_2O$ ), where all pollutants are measured in kilograms [kg]. These impact categories were used for both the WTP and operation only data to maintain consistency and allow for an overall summation of total impacts. Separate emission factors were calculated for each impact category for both WTP and

operation only, where an *emission factor* was a term coined for this study as coefficients that can be multiplied by the number of miles driven to yield the amount of pollutant emitted or resource used to drive that distance for a particular vehicle bin. Emission factors were ultimately used to calculate the environmental impact of driving for both data sets—the NHTS data and the survey.

In addition to the ten impact categories above, PM10 emissions were also calculated using the developed methodology. These results and discussions were withheld from the main body of this paper and presented in the Appendix due to anomalous behavior in year-over-year changes in WTP emission factors. This behavior was not an artifact of the methodology developed in this study nor of the data collected from the surveys, but rather was traced back to the data in the GREET database. The GREET datasets were treated as fixed values in this study, where the data was used as is, and not calculated or modified, thus meaning anomalous behavior in the data could not be rectified. The data of concern produced substantial increases in PM10 between years 1999 and 2004 while all the other ten impact categories either exhibited appreciable decreases or near-zero-changes during that period. With no reasonable explanation for this singular increase specific to PM10 with respect to combustion technology and chemistry, these results were moved to the Appendix.

#### *3.2.3.1 FUEL CYCLE EMISSION FACTORS*

The WTP data set was obtained by selecting *Gasoline* under the *Products* list in GREET, then refining the selection to *E10*, where E10 is a gasoline blend with ten percent ethanol content. E10 was selected since it is the standard fuel blend in the United States, and ethanol comprised approximately ten percent by volume of motor gasoline sold in the U.S. (U.S. Energy Information Administration, 2016). One gallon of E10 was selected as the functional unit by

which to measure the GREET outputs. This was then converted to an impact per mile unit—emission factor—by dividing by the standardized vehicle fuel efficiency values to convert the data from impact per gallon to impact per mile. The emission factors were calculated according to Equation 2.

$$F_x = \frac{E_x}{e_z} \quad (2)$$

$F_x$  is emission factor (amount/mile) for pollutant or resource  $x$  and amount is mass of pollutant, volume of water, or energy and  $E_x$  is emission per gallon of pollutant  $x$  or resource use per gallon of resource  $x$  from GREET.

Separate emission factors were calculated for each vehicle type at each model year for all pollutants or resources within the WTP data set. The large quantity of emission factors is a direct result of the standard fuel efficiency values differing among vehicle type and model year, producing a set of emission factor matrices. Figure 11 outlines the process of determining the emission factors and employing them to calculate impacts. Table 6 exhibits the matrix of emission factors for CO<sub>2</sub> emissions for all study vehicle types and model years, where emission factors are in units of kg CO<sub>2</sub>/mile. The emission factor matrices for the other pollutants and resources can be found in the appendix.

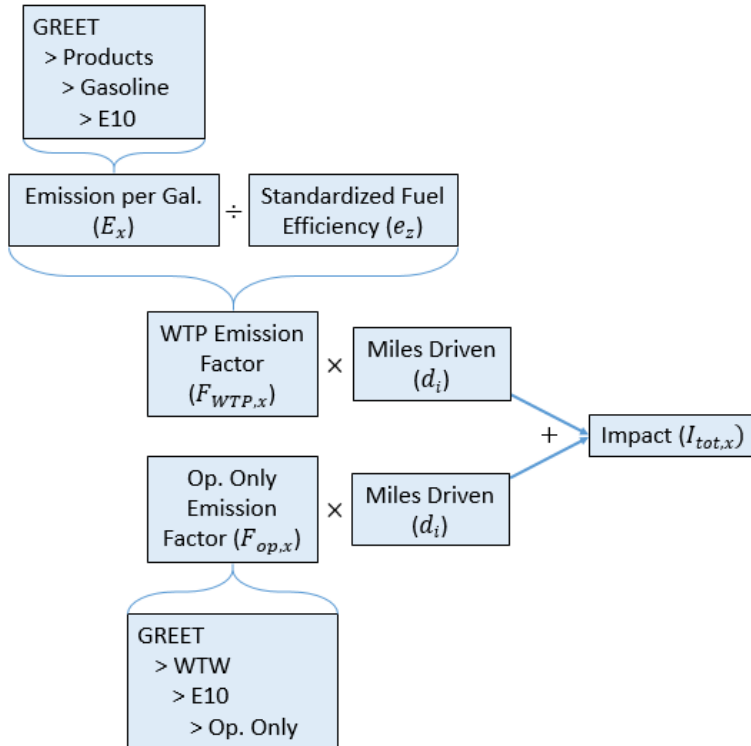


FIGURE 11. PROCESS OF DETERMINING EMISSION FACTORS AND PATH OF IMPLEMENTATION.

TABLE 6. EMISSION FACTORS FOR CARBON DIOXIDE.

		Vehicle Type							
		Large PUT	Small PUT	SUV	Hybrid SUV	Large Sedan	Small Sedan	Hybrid Sedan	Coupe
Model Year	<1980	1.451E-1	1.087E-1	1.310E-1	NA	1.154E-1	9.553E-2	NA	1.097E-1
	1980-1989	1.451E-1	1.087E-1	1.310E-1	NA	1.154E-1	9.553E-2	NA	1.097E-1
	1990-1999	1.451E-1	1.087E-1	1.310E-1	NA	1.154E-1	9.553E-2	NA	1.097E-1
	2000-2004	1.440E-1	1.102E-1	1.357E-1	NA	1.118E-1	9.674E-2	4.717E-2	9.194E-2
	2005-2009	1.420E-1	1.138E-1	1.273E-1	8.268E-2	1.126E-1	9.250E-2	5.425E-2	9.809E-2
	2010-2014	1.407E-1	1.087E-1	1.092E-1	8.591E-2	1.073E-1	8.230E-2	5.609E-2	8.808E-2
	2015-2016	1.260E-1	1.014E-1	1.034E-1	7.524E-2	1.031E-1	8.106E-2	5.528E-2	9.422E-2

### 3.2.3.2 OPERATION ONLY EMISSION FACTORS

The second portion of the use phase impact assessed in this study was the environmental impact of exclusively fuel combustion. Under the *WTW* banner in GREET, *E10* was selected as the fuel type under which to subsequently select vehicle types, and data was extracted from the *Operation Only* column. The GREET data was vehicle type-dependent, implicating each vehicle

type would have its own emission factor and the standardized fuel efficiency coefficients presented in section 3.2.2 would not be used. Consequently, a different process than that developed to calculate the WTP emission factors was needed for the operation only data. The impact data gathered from GREET was used directly as the emission factor, as it had the appropriate functional unit of amount of pollutant/resource per mile. Separate WTW datasets were used for different vehicle technology years, accomplished by selecting *Simulation Parameters* and altering the *Vehicle Tech Lag* field to generate data for the desired year. The year ranges used reflected those implemented in the WTP section, and the operation only data for each range was that of the oldest model year in each range—for example, operation only data for 2005 was used for all years in the 2005-2009 range. Table 7 presents the large pickup truck (PUT) operation only emission factors in units of MJ energy/mile, cm<sup>3</sup> water/mile, or kg pollutant/mile. The operation only emission factor matrices for the other vehicle types can be found in the appendix.

**TABLE 7. OPERATION ONLY EMISSION FACTORS FOR LARGE PICKUP TRUCKS.**

Year Range	Total Energy (MJ)	Total Water Use (m <sup>3</sup> )	VOC (kg)	CO (kg)	NO <sub>x</sub> (kg)	PM2.5 (kg)	SO <sub>x</sub> (kg)	CH <sub>4</sub> (kg)	CO <sub>2</sub> (kg)	N <sub>2</sub> O (kg)
2015-2016	5.23E+0	0.00E+0	1.60E-4	7.48E-3	4.60E-4	1.03E-5	0.00E+0	1.63E-5	3.70E-1	1.14E-5
2010-2014	5.96E+0	0.00E+0	1.80E-4	7.63E-3	5.10E-4	1.04E-5	0.00E+0	1.70E-5	4.20E-1	4.14E-5
2005-2009	8.01E+0	0.00E+0	5.00E-4	1.88E-2	2.70E-3	1.04E-5	0.00E+0	8.19E-5	5.50E-1	4.15E-5
2000-2004	8.70E+0	0.00E+0	1.03E-3	1.81E-2	3.38E-3	1.92E-5	0.00E+0	5.52E-5	6.00E-1	9.26E-5
1990-1999	8.83E+0	0.00E+0	2.05E-3	2.20E-2	2.72E-3	4.56E-5	0.00E+0	9.28E-5	6.00E-1	5.40E-5
1980-1989	8.83E+0	0.00E+0	2.05E-3	2.20E-2	2.72E-3	4.56E-5	0.00E+0	9.28E-5	6.00E-1	5.40E-5

It can be observed that total water use and SO<sub>x</sub> emissions are zero. Water consumption is an important consideration in the fuel cycle, however the combustion phase does not consume water. GREET does not identify sulfur as a discernable component in E10, which explains the

zero value for the operation only SO<sub>x</sub> emission factor; ethanol contains no sulfur, and gasoline inherently has minimal sulfur content (Wu et al, 2004). SO<sub>x</sub> is emitted during the fuel cycle through combustion of sulfur-containing fuels such as coal, which provides significant amounts of the energy needed in the extraction and refinement processes, and this is reflected in the WPT SO<sub>x</sub> emission factor.

### 3.2.3.3 TOTAL IMPACT—NHTS

Prior to multiplying each emission factor by number of miles driven to obtain an impact estimate, it was necessary to translate the NHTS vehicle type classification into the vehicle types represented in the WTP and operation only emission factor matrices. The listing of NHTS vehicle types and the corresponding study vehicle type can be found in the appendix. Data without a vehicle type listed were assigned emission factor data for a large sedan, and missing model years were assigned 2004. The determination to use large sedan to fill in missing vehicle types was based on its standardized mpg data being a median value among all vehicle type mpg values, and the same rationale for using 2004 was employed, that is was the median model year. Number of miles driven for each participant was determined by the *Best Estimate of Annual Miles* field, and when absent, the *Self-Reported Annualized Miles Estimate* was used. Data with neither field available was assigned the average value of the *Best Estimate of Annual Miles* field. An average was opted for over a distribution solely for ease of calculation. The miles driven for each participant was multiplied by the emission factors to produce an environmental impact value for each impact category for NHTS years 1990, 1995, 2001, and 2009.

Each participant had a weighting factor provided in the NHTS dataset that determined the percentage of the total study area population represented by that participant. The impacts of each

individual NHTS data point were multiplied by the respective weighting factors to generate an impact for the general population. The total impact of the general population was obtained via a summation of the weighted WTP and operation only impacts, which was completed for each impact category. The total impact of the overall population is described by

$$I_{WTP,x} = \sum_{j=1}^p F_{WTP,x} \cdot d_i \cdot w_i \quad (3)$$

$$I_{op,x} = \sum_{j=1}^p F_{op,x} \cdot d_i \cdot w_i \quad (4)$$

$$I_{tot,x} = I_{WTP,x} + I_{op,x} \quad (5)$$

where  $I_{WTP,x}$ ,  $I_{op,x}$ , and  $I_{tot,x}$  is WTP impact, operation only impact, and total impact of the overall population, respectively, for pollutant/resource  $x$  in mass of pollutant, volume of water, or energy;  $p$  is the number of survey participants;  $d_i$  is the distance travelled by participant  $i$  in miles; and  $w_i$  is the weighting factor of participant  $i$ . Equations 3, 4, and 5 can be combined into a single equation that demonstrates the total impact for the overall study area population:

$$I_{tot,x} = \sum_{j=1}^p (F_{WTP,x} + F_{op,x}) \cdot d_i \cdot w_i \quad (6)$$

Equation 6 illustrates that WTP and operation only calculations can be combined by adding the two respective emission factors prior to generating separate impacts. This methodology was applied to each impact category through the different corresponding emission factors for NHTS data from survey years 2009, 2001, 1995, and 1990, where the 2009 and 2001 data represented the state of Wisconsin and the 1995 and 1990 data pertained to the Milwaukee MSA only. Total

annual miles travelled estimates for the general population were calculated by summing the products of each miles travelled data point multiplied with its weighting factor. This was then divided by population estimates from the United States Census Bureau (2016) and the Economic Research Division (2014) [Metropolitan Milwaukee Association of Commerce] to establish an estimate of miles travelled per person. Respondents for the 1990 and 1995 surveys with annual mile estimates recorded as 999,999 were assigned an annual mile estimate of the average of all participants' annual mile estimates omitting all 999,999 values (12,428 miles for 1995 and 11,436 miles for 1990); values of 999,999 were dummy values used in the survey and were not to be used directly as were the 0-200,000 values, as indicated in the NHTS code book.

#### *3.2.3.4 TOTAL IMPACT—SURVEY*

As with the environmental impacts from the NHTS, the impacts from the administered survey were obtained by multiplying the emission factors with miles driven. Miles driven data were obtained directly from the survey responses, where participants indicated how many miles they drove on a per vehicle basis. Weekly mileage range bins were provided from which the respondents chose—1-24, 25-49, 50-99, 100-149, 150-199, 200-249, and 250+. All impact calculations from the survey data that included miles driven were computed with a low mileage bound, middle mileage value, and a high mileage bound. The low and high bounds were the respective extreme values of each range, and the middle value was the median of the mileage range. For example, considering the 1-24 miles range, the low bound was one mile, the middle value was 12.5 miles, and the high bound was 24 miles. A table of all mileage ranges can be found in the appendix. This was done to represent the variability in the data arisen from the use of mileage ranges rather than discrete, single values. Equation 6 can be employed to provide a

process by which to calculate the total environmental impact of the general study area population using middle mileage values and low and high bounds.

#### *3.2.4 REBOUND CALCULATIONS FROM SURVEY*

As understood from 3.2.1, a rebound is an increase in consumption of a good or service as the price of that good decreases through increased efficiency. To get an estimate of the rebound, the growth rate of consumption is to be divided by the efficiency growth rate, as expressed generally in Equation 7.

$$R = \frac{\Delta c/c}{\Delta e/e} \quad (7)$$

$R$  is the rebound,  $c$  is consumption level and  $e$  is efficiency, mirroring the rebound calculation structure presented in Dahmus (2014). The percent change in efficiency ( $\Delta e/e$ ) was determined by utilizing data from the survey responses, where respondents indicated their current vehicle type and model year along with the vehicle type of their next purchase. The model year of the vehicles to be purchased was not available, so the 2010-2014 mpg values were applied to the appropriate vehicle type. This was determined to be a reasonable intermediate value, since many used vehicles may likely fall into this bin, and the standardized mpg values of most new vehicles would be similar to the 2010-2014 values. The change in standardized mpg values for the respective vehicles was used to calculate  $\Delta e/e$  for every participant who indicated a future vehicle purchase; respondents with no anticipated purchase generated a value of zero. All rebound values calculated in this study correspond to an overall population rebound rather than a series of rebounds for each individual consumer.

The survey collected data reflecting the extent to which each respondent would anticipate altering driving habits in response to adoption of a vehicle perceived to be more fuel efficient. Respondents who indicated they would purchase another vehicle at some future time selected among no increase, 25% increase, or 50% increase in miles driven; participants with no intention of purchasing another vehicle did not receive this question due to them not acquiring an additional vehicle with which to analyze a rebound or the lack thereof. This study calculated a fuel consumption rebound, a miles driven rebound, and an environmental impact rebound, where the environmental rebound was expressed as the percent increase of the expected pollution reduction or resource use based on the impact categories presented in 3.2.3. The fuel consumption rebound for each participant followed

$$R_{fuel} = \frac{\Delta f/f}{\Delta e/e} \quad (8)$$

where

$$\frac{\Delta f}{f} = \frac{\sum_{j=1}^p \left[ \left( \frac{d_{1,i}(1+\alpha_i)}{e_{2,i}} - \frac{d_{1,i}}{e_{1,i}} \right) \cdot w_i \right]}{\sum_{j=1}^p \left[ \frac{d_{1,i}}{e_{1,i}} \cdot w_i \right]} \quad (9)$$

and

$$\frac{\Delta e}{e} = \sum_{j=1}^p \left[ \frac{e_2 - e_1}{e_1} \cdot \omega_i \right] \quad (10)$$

where  $f$  is amount of fuel consumed, determined by dividing distance travelled by participant  $i$  ( $d_i$ ) by fuel efficiency ( $e_i$ );  $\alpha_i$  is the anticipated percent increase in miles driven following adoption;  $w_i$  is the participant weighting; and  $\omega_i$  is the participant weighted average. A weighted

average was implemented in order to maintain the percent change format while incorporating each participant's population weighting. Participants who indicated no intended purchase generated  $\Delta f/f$  equaling zero. A rebound for the entire population was calculated by dividing the total population's aggregate percent change in fuel consumption by its aggregate percent change in efficiency. These calculations show that fuel consumption rebound was determined by applying household-specific rebound data to the corresponding household-specific mileage data, which in turn was implemented to calculate a rebound for the population.

Similarly, the environmental impact rebound, denoted as  $R_{EI}$ , was calculated with

$$R_{EI} = \frac{\sum_{j=1}^p \left[ \frac{\Delta \varepsilon}{\varepsilon} \cdot \omega_i \right]}{\sum_{j=1}^p \left[ \frac{\Delta e}{e} \cdot \omega_i \right]} \quad (9)$$

where  $\Delta \varepsilon/\varepsilon$  is the percent change in amount of pollutant emitted or resource used before and after adoption, respectively. Emission/resource use before adoption ( $\varepsilon_1$ ) is given by

$$\varepsilon_1 = F_x \cdot d_i \cdot w_i = I_{tot,x} \quad (10)$$

and the emission/resource use after adoption was determined by multiplying  $\varepsilon_1 \times (1 + \alpha)$ . Upon mathematical simplification, it will be seen that the percent change in impact ( $\Delta \varepsilon/\varepsilon$ ) is equal to the percent change in miles driven after adoption ( $\alpha$ ). Furthermore, the environmental rebound is equivalent for all pollutants and resources because emissions [and changes thereof] are dependent purely on miles driven. Similar to the fuel consumption rebound, the environmental impact rebound was calculated using weighted averages for individual participants, and the general population rebound was determined by dividing the weighted average population percent change in emissions by the weighted average population percent change in efficiency.

The miles driven rebound calculation followed the same process outlined in Equation 7, where the population percent change in miles driven was divided by the population percent change in efficiency, as shown in Equation 11.

$$R_d = \frac{\Delta d/d}{\Delta e/e} \quad (11)$$

The percent change in miles driven ( $\Delta d/d = \alpha$ ) was directly attained from the survey. In addition to calculating the fuel consumption and environmental impact rebounds for the general population, separate rebounds were decomposed into two groups based on geographical location of residence: a rural group and an urban/suburban group.

### **3.3 RESULTS AND DISCUSSION**

#### *3.3.1 NHTS ENVIRONMENTAL IMPACT*

Calculations of the environmental impacts for the four survey years allowed for temporal comparisons to be made to offer insight into changes in emission rates and levels of resource use. Data is presented for each NHTS year for the total impact, the change in total impact, per person impact, and change in per person impact for both the state of Wisconsin and the Milwaukee MSA. State-wide data for 1995 and 1990 were not available, so the included Milwaukee MSA data was used.

When assessed at the Wisconsin state level, Figure 12 presents the six pollutants that exhibited a decrease in total impact and eight impact categories that decreased on per person basis. A table containing data for all impact categories and their respective percent changes can be found in the appendix. These trends coincide with a small population increase from 5,363,675 to 5,686,986 (approximately 6%) (United States Census Bureau, 2016) and a similarly small increase in total

miles driven from 47,643,496,764 to 50,408,080,895. Miles driven per person stayed nearly static, changing from 8,883 to 8,864. These data make it tempting to associate the decrease in vehicle emissions with improvements in automobile technology, since vehicles have displayed continual improvements in fuel efficiency (DOE, 2015). Additionally, the nearly static level of miles driven per person may suggest that a substantial rebound is not likely to be exhibited, as these estimates imply drivers did not increase their miles driven while fuel efficiency generally improved. This may furthermore suggest that the efficiency-improving technological innovations in the years leading up to 2009 have been sufficient to counteract the increase in population and the corresponding increase in miles driven without causing an extensive increase due to a rebound.

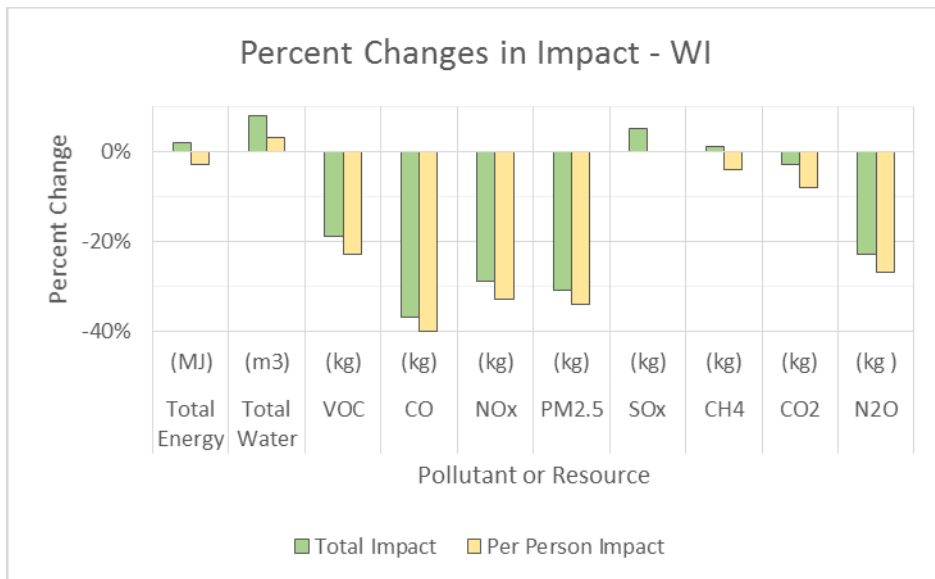


FIGURE 12. PERCENT CHANGE IN IMPACT BETWEEN 2001 AND 2009 IN STATE OF WISCONSIN.

The decrease in total amount of pollutant emitted from 2001 to 2009 for six of the studied impacts may offer promise in the effort to reduce the deleterious impacts of air pollution from personal transportation in the coming years. The notion that modest growth in population size

and vehicle miles travelled can be counteracted by improvements in fuel economy implies legislations such as the CAFE standards have been successful in reducing the amount of certain pollutants emitted. It is relevant to consider, however, that the increase in consumption and miles driven cannot outpace the improvements in efficiency if emission reductions are to be achieved.

To meet this requirement, attention can be paid to maintaining a small growth rate in miles driven—or a reduction, larger improvements in efficiency, or a combination thereof. The apparent dearth of a rebound in per person emissions maintains efficiency improvements as a viable option, as the would-be savings from efficiency do not appear to be negated from an increase in consumption. Initiatives to decrease miles driven include increased consumption of alternate transportation, including public transit and changes in personal driving behavior such as combining trips and carpooling (Wu et al, 2011). These initiatives can be achieved through infrastructure design that includes comprehensive public transit systems—bus or rail—and widespread bicycle and walking lanes. A tax on fuel or on fuel-inefficient vehicles can also be implemented as an attempt to decrease fuel consumed via supply and demand economics: the increase in price will push down demand for those goods. A combination of reducing emissions per mile driven through improved efficiency and reducing miles travelled can promote a beneficial reduction in transportation emission levels.

On the metropolitan level, an increase in impact was exhibited for all impact categories studied for both total impact and per person impacts, as shown in Figure 13. A table containing data for each impact category considered is provided in the appendix. This time period displayed a 2.4% population growth from 1,432,149 to 1,466,447 (Economic Research Division, 2014), an 8.3% increase in total miles travelled from 9,955,998,339 to 10,784,421,095, and a 5.8% increase in miles travelled per person from 6,952 to 7,354. The percent increase of total impact ranged from

13% for total water to 27% for CO and on a per person level, 13% for total water to 26% for CO. It cannot be ascertained whether or not a rebound existed during this time window due to the lack of data on individual vehicle adoption for each participant between the two survey years, however, it can be observed that the percent increase for each resource/pollutant was greater than the percent increase in miles driven.

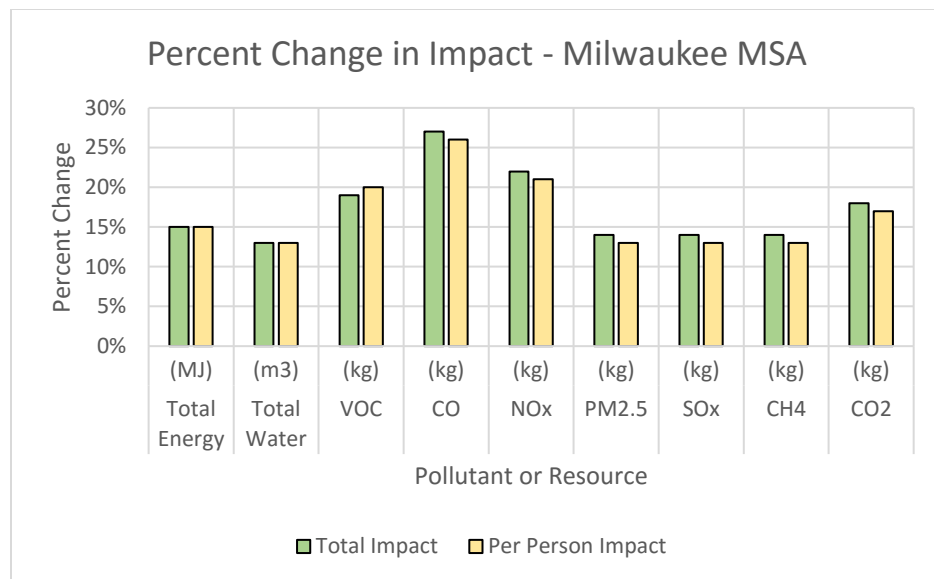


FIGURE 13. PERCENT CHANGE IN IMPACT BETWEEN 1990 AND 1995 IN MILWAUKEE MSA.

As emissions of pollutants increase, it can be pertinent to understand the air quality standards implemented via legislation. The US EPA issued National Ambient Air Quality Standards (NAAQS) as part of the Clean Air Act that outline the legal, acceptable outdoor air concentrations of six criteria air pollutants: CO, lead, NO<sub>2</sub>, O<sub>3</sub>, PM, and SO<sub>2</sub>. NAAQS are partitioned into primary standards, which focuses on public health protection, and secondary standards, pertaining to public welfare—visibility and property damage. The standards are occasionally updated, where the current limits were implemented in 2008, as presented in Table 8 (US EPA, 2016). When concentrations of any criteria pollutant exceeds the standard for a

geographic location, that area is considered a nonattainment area. According to the EPA, none of the three locations analyzed in this study were nonattainment during the respective time periods of study. In Wisconsin, there have been only three cases of nonattainment: 8-hour ozone in Kenosha County in 2008, SO<sub>2</sub> in Oneida County in 2010, and 8-hour ozone in Sheboygan County in 2008 (US EPA, 2016). The dearth of nonattainment episodes in Wisconsin may suggest that small increases in concentrations of criteria pollutants may not have a deleterious effect on human health and welfare.

**TABLE 8. CURRENT NAAQS SET BY THE US EPA IN 2008 (US EPA, 2016).**

Pollutant	Type	Standard	Average Timing
SO <sub>2</sub>	Primary	75 ppb	1-hour
SO <sub>2</sub>	Secondary	0.5 ppm (1,300 µg/m <sup>3</sup> )	3-hour
PM10	Primary and Secondary	150 µg/m <sup>3</sup>	24-hour
PM2.5	Primary	12 µg/m <sup>3</sup>	Annual
PM2.5	Secondary	15 µg/m <sup>3</sup>	Annual
PM2.5	Primary and Secondary	35 µg/m <sup>3</sup>	24-hour
CO	Primary	35 ppm (40 mg/m <sup>3</sup> )	1-hour
CO	Primary	9 ppm (10 mg/m <sup>3</sup> )	8-hour
O <sub>3</sub>	Primary and Secondary	0.12 ppm (235 µg/m <sup>3</sup> )	1-hour
O <sub>3</sub>	Primary and Secondary	0.070 ppm (140 µg/m <sup>3</sup> )	8-hour
NO <sub>x</sub>	Primary and Secondary	0.053 ppm (100 µg/m <sup>3</sup> )	Annual
Pb	Primary and Secondary	0.15 µg/m <sup>3</sup>	Rolling 3 months

With the growth rate of the impacts being disproportionately larger than the population growth rate and that of per person miles driven, it would appear that vehicle fuel efficiency worsened rather than improved for drivers in the Milwaukee area from 1990 to 1995. During this time, average new vehicle fuel economy decreased from approximately 26 mpg to around 24 mpg (PEW Charitable Trusts, 2011) while fuel prices decreased by an average of \$0.19/gallon, which may have influenced the increase in miles driven. Average gasoline prices in the US in 1990 were \$1.30/gal, \$1.11/gal in 1995, \$1.42/gal in 2001, \$2.35/gal in 2009, and \$1.86/gal in 2016, where Wisconsin prices closely mirrored national prices (Statista, 2016; GasBuddy.com, 2016;

American Automobile Association, 2016). The trend of increased impacts observed in Figure 13 appears to be due to both the increase in miles driven per person and the decrease in fuel efficiency during that period.

Although the pattern of increased impacts is undesirable in the context of reduction of air pollution and environmental impact, it does leave substantial potential for improvement from top-down fuel economy standards. That vast potential, in conjunction with the relatively small increase in per person miles driven, outlines an adequate method for potentially reducing vehicle emissions while the population continues to grow. With the benefit of hindsight, it can be observed that fleet fuel economy has improved since 1995, as exhibited in Table 5. The results of these improvements can loosely be seen in Figure 12, where the change in various impacts has decreased from 2001 to 2009 for Wisconsin drivers.

### *3.3.2 ENVIRONMENTAL IMPACT FROM SURVEY*

The methodology employed to determine the environmental impact and degree of rebound from the NHTS data was applied to the data collected from the administered survey. A comparison between the MMSA and Wisconsin as a whole yields Madison area drivers generate a smaller annual impact in all impact categories excepting PM<sub>2.5</sub>, as observed in Figure 14. This may not be a surprise considering the study data was collected in 2016, while the NHTS data was released in 2009 and 2001, creating a temporally uneven comparison; the seven to fifteen intervening years is likely to lead to a disparity between vehicle model years, where presumably older vehicles impart a larger environmental impact. Additionally, residents in the MMSA have more access to alternate modes of transportation due to their urban residence than the average driver in Wisconsin, in large part a result of the expansive rural areas. A comparison between the

impacts of Madison area drivers and Milwaukee area drivers results in an even larger difference in impacts than that between the MMSA and WI. The incongruence between the ages of the data is yet more pronounced, as the Milwaukee MSA data was released in 1995 and 1990. Both locations are urban, however, and do have realistic alternate transportation options available. The average fuel economy from 1990 to 2015 across all vehicle types in this study exhibited an increase, growing from 18.8 mpg to 24.8 mpg, based on the standardized fuel economy bins presented in Table 5.

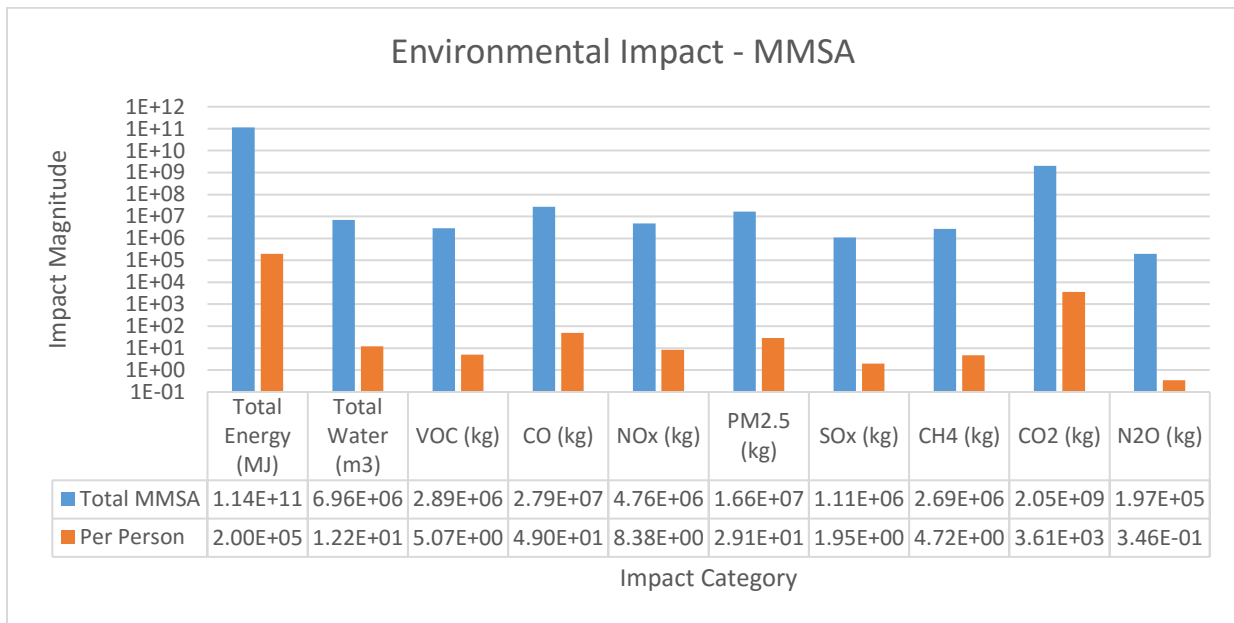


FIGURE 14. TOTAL IMPACT FOR MMSA AND PER PERSON.

Drivers in the MMSA were calculated to drive on average 10,464 miles per year, which is slightly greater than the average 8,864 and 8,883 miles of 2009 and 2001 Wisconsin drivers, respectively, and larger than the 1995 and 1990 Milwaukee MSA population weighted annual average of 7,354 and 6,952 miles, respectively, as compared in Table 8. In Table 8, the Wisconsin population size for 2009 is from year 2010 and the 2001 population size is from year 2000 due to census limitations. Average fleet fuel efficiency was determined by computing the

average fuel economy of all mpg bins for each year (see section 3.2.2 and Table 5). The national annual vehicle miles traveled per driver is noticeably greater, where it increased from approximately 13,000 miles in 1990 to 14,000 miles in 2009 (U.S. Department of Transportation Federal Highway Administration, 2014). This suggests the distance that people drive has been increasing over time. Temporal fuel price changes may be a factor influencing the changes in personal miles driven among the study years. The average fuel prices during each of the study years presented in 3.3.1 indicates gasoline prices have experienced multiple inflection points during that time. It may be expected that an increase in fuel price would coincide with a decrease in miles driven and vice-versa. This expectation held true for years 1990-1995, 2001-2009, and 2009-2016; years 1995-2001 exhibited an increase in gasoline price and an increase in miles driven.

**TABLE 9. 2016 POPULATION OF MMSA AND PER PERSON AND TOTAL MILES DRIVEN.**

Year	Location	Population Size	Total Miles Travelled	Per Person Miles Travelled	Average Fleet Fuel Efficiency (mpg)
2016	MMSA	568,593	5,950,018,604	10,464	24.8
2009	Wisconsin	5,686,986	50,408,080,895	8,864	22.8
2001	Wisconsin	5,363,675	47,643,496,764	8,883	23.2
1995	Milwaukee MSA	1,466,447	10,784,421,095	7,354	18.8
1990	Milwaukee MSA	1,432,149	9,955,998,339	6,952	18.8

The witnessed trend of increased miles driven per person matched with continual population growth creates a two-pronged condition of increasing amounts of total pollution. Concentrating growing numbers of people while simultaneously rising their personal transportation activities and the corresponding air pollution generates the distinct need to manage emissions in attempt to mitigate current and future air pollution problems. One of the largest problems associated with air quality is human health, which can be profoundly impacted by proper air quality management. Figure 15 summarizes the per person impacts NO<sub>x</sub> and CO<sub>2</sub> over the duration of

the study years. CO<sub>2</sub> emissions stay relatively constant over the 26 years, while NO<sub>x</sub> emissions exhibit a distinct decrease, on the level of two orders of magnitude. This trend may be driven by the widespread implementation of three-way catalytic converters, which convert carbon monoxide (CO) and VOCs into CO<sub>2</sub> and water and NO<sub>x</sub> into N<sub>2</sub>. Although this technology was first introduced in new vehicles prior to 1990, it may have taken numerous years until all older vehicles were phased out and no longer on the road, creating the lag in decrease in NO<sub>x</sub> emissions seen in Figure 15, where all values are in units of kilograms (Zeng & Hohn, 2016).

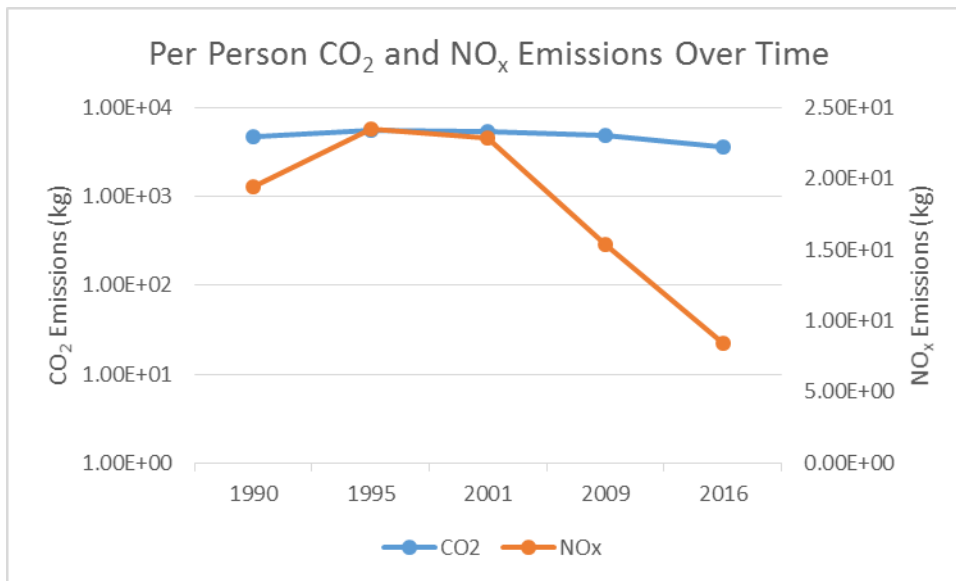


FIGURE 15. EMISSIONS PER PERSON FOR NO<sub>x</sub> AND CO<sub>2</sub> FOR EACH STUDY YEAR.

### 3.3.3. REBOUND ESTIMATE FROM SURVEY

Rebound estimates were calculated in the context of amount of fuel consumed as well as for environmental impact—certain pollutant emission and resource use. The environmental impact rebound expresses the percent change in pollutant emitted (or resource used) between the anticipated and actual emission (or use) level due to the change in miles driven following adoption. In other words, the rebound value expresses the percent of anticipated emission (or

resource use) savings that were eroded, or given back from the change in consumption. All rebounds were calculated for the population as a whole as well as rural and non-rural (suburban plus urban) groups.

Figure 16 summarizes the fuel consumption rebounds, calculated using the methodology presented in Dahmus (2014), where percent change in consumption was divided by percent change in efficiency (see section 3.2.4). It can be observed that there was a large difference in driving activity after adoption with respect to residential location. The rural group had the smallest rebound while the urban/suburban (non-rural) group had the largest rebound, and the total population resided between. Both the total population and the non-rural group exhibited rebounds larger than 100%, which indicates the adoption of fuel efficient vehicles led to both an increase in miles driven and, more importantly, an increase in fuel consumed. On the converse, the rural group produced a negative rebound value, which corresponds to a reduction in miles driven and fuel consumed following adoption.

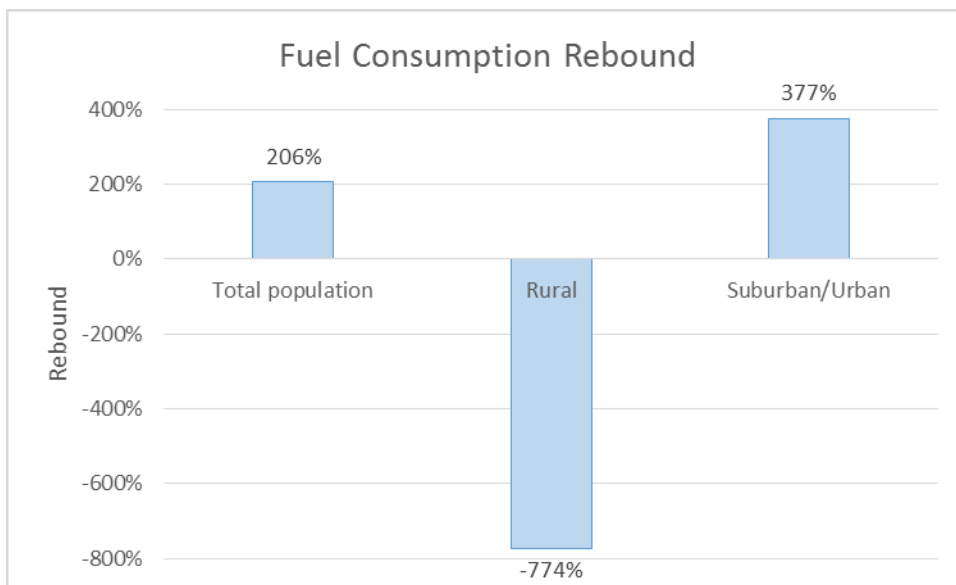


FIGURE 16. FUEL CONSUMPTION REBOUND FOR ENTIRE POPULATION, RURAL GROUP, AND NON-RURAL GROUP.

A potential explanation for these rebound trends are that multiple methods of alternate transportation are readily available to urban residents, to which their rural counterparts do not have access. When urban drivers own fuel inefficient vehicles, they may be more prone to use a different form of transportation—walking, cycling, bus route, or rail line—as a cost savings measure. The adoption of a more fuel efficient automobile may goad a portion of these drivers to decrease their consumption of alternate transportation and increase their amount of miles driven, causing a rebound. Rural drivers are less apt to exhibit the same behavior because they likely do not have the same level of robust access to the sundry types of alternate transportation; bus and rail routes do not typically span into rural regions, and walking and cycling as a commuting option is often not feasible because of the prohibitively long distances. As a result, rural commuters who own a fuel inefficient automobile cannot realistically reduce their use of that vehicle by opting for other transportation methods. Thus, when these drivers adopt a more fuel efficient vehicle, they may be more likely to display a smaller rebound than urban drivers.

Fuel consumption can be decomposed into constituent emissions and resources used associated with production and combustion of the given amount of fuel. When assessing fuel consumption by the environmental impact, the non-rural group maintained the largest rebound at 260%, with the total population rebound being slightly smaller at 213%, and the rebound of the rural group was noticeably less (30%), as presented in Figure 17. A notable change from the fuel consumption rebound is all rebounds are positive, indicating an increase in the anticipated impacts. Additionally, the spread among the different groups' rebounds is smaller than with the fuel consumption rebounds.

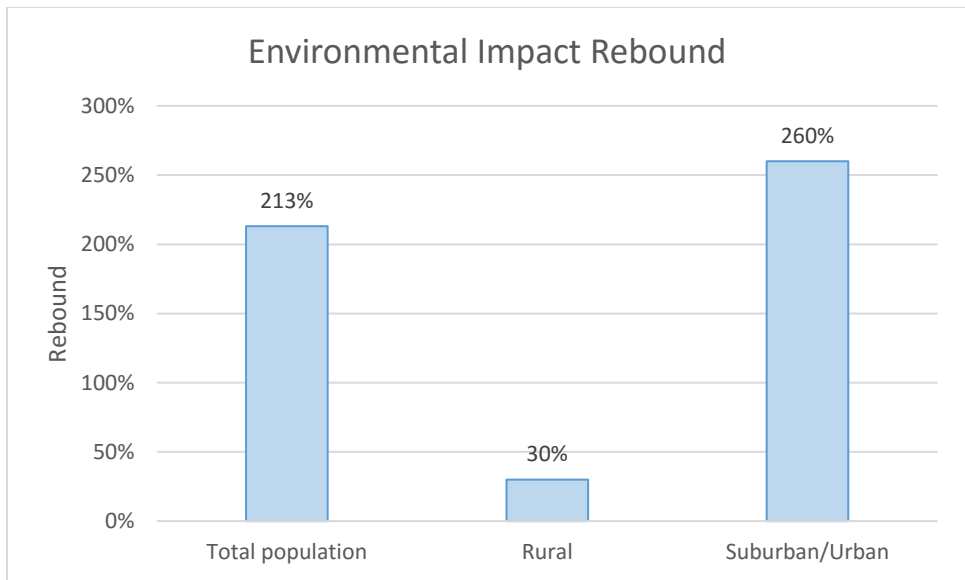


FIGURE 17. ENVIRONMENTAL IMPACT REBOUNDS FOR TOTAL POPULATION, RURAL GROUP, AND NON-RURAL GROUP.

Determining which types of geographical regions—rural or suburban/urban—exhibit a larger rebound can give insight into which regions on which to focus for air pollution reduction and the nature of the associated impacts. Air pollution impacts in a location with higher population density—urban or suburban locales—may have a significant impact on human health, whereas air pollution in less populated rural regions may not impact human health significantly due to the pollutant concentration dilution and dispersion, but may rather have a more global, distributed impact (Cohen et al, 2004). Considering the larger rebound found for suburban/urban regions, it suggests that improvements in vehicle fuel efficiency may lead to increases in urban/suburban air pollution and a consequent increase in related human health ailments.

When assessing the rebound with respect to miles driven, the rural group exhibited the largest rebound (846%), the suburban/urban group hosts a rebound of 304%, and the rebound of total population is 202%, as presented in Figure 18. These results implicate that all three groups increased their miles driven at a more rapid rate than their fuel efficiency improved, suggesting

an overall net increase. An interesting note to observe is that the rural fuel consumption rebound is negative (-774%), while the miles driven rebound for that same group is positive (846%). This may be an artifact of drivers adopting vehicles that are *less* efficient, where some consumers' perception of improved efficiency may lead them to adopt a vehicle that is less fuel efficient. This, in part, may come from consumers placing a higher value on other automobile attributes than fuel economy. The discrepancy between perceived efficiency improvement and actual fuel efficiency improvement may be a source of variability in rebound calculations.

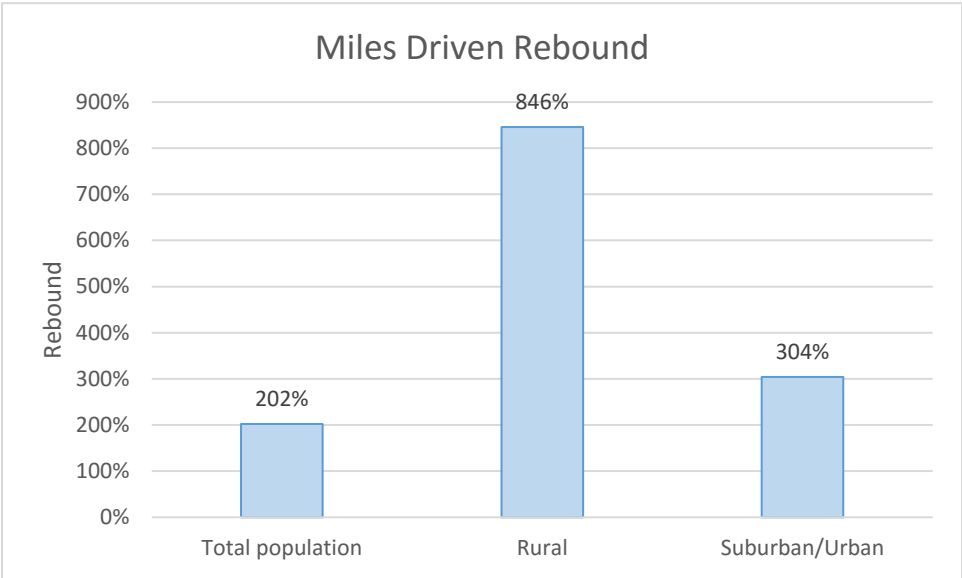


FIGURE 18. MILES DRIVEN REBOUNDS FOR TOTAL POPULATION, RURAL GROUP, AND NON-RURAL GROUP.

The magnitude of the rebound estimates in this study resemble those presented in Dahmus (2014), where 1940-2009 motor vehicle travel rebound was approximated to be 1000% with regards to distance travelled. Dahmus (2014) also issued rebounds for nine other industries, which ranged from 110% to 830%. As discussed in 3.2.4, the rebounds in both this research and in Dahmus (2014) were calculated by dividing the percent change in quantity (consumption) by the percent change in efficiency. This differs from the 5-65% range in the literature (see section

3.1) mainly due to variability in calculation methods. Other studies incorporate elasticity of fuel and fuel demand in their calculations as well as other econometric functions. For instance, Saunders (2013) calculated the rebound by dividing the elasticity of substitution (between energy and other production factors) by one minus the *energy value share*. He states that by including all factors, not just those pertaining to energy inputs, it would “[create] a condition of energy consumption “backfire”—technology improvements *increased* energy consumption rather than decreased it.” (Saunders, 2013). Frondel et al (2012) formulated their rebound by taking the partial derivative of the natural log of the *service demand* with respect to the natural log of the service demand divided by the energy input. Hymel & Small (2015) calculated the rebound as a function of price index of new vehicles, cost of fuel per mile, regulatory variables, vehicle miles traveled elasticity, and a host of exogenous variables and constants. It can be observed that the numerous methods for estimating the rebound encompass many different factors, which has the potential to yield varying values for the rebound.

Rebounds of the magnitude of those found in this study—generally greater than 100%—indicate societal driving levels may be prone to increase by a substantial margin. However, it was found that drivers are heterogeneous, where a subset of drivers displayed a propensity to greatly increase their driving, and other consumers produced a small or no rebound which effectually pulled down the population rebound. Understanding this heterogeneity may help to identify the route to most effectively reduce the rebound, where targeting the particular faction of drivers who exhibit a large rebound may yield a much more fruitful result than attempting to reach all drivers.

The large societal rebound implicates that improvements in fuel efficiency in personal vehicles may likely cause a sharp increases in consumption, and legislation mandating stricter fuel

efficiency standards may not achieve their targets of reducing fuel consumption. Locations with air pollution problems caused by heavy vehicle traffic may worsen the problem, rather than mitigate it, by implementing wide spread adoption of fuel efficient vehicles. Considering the rebounds were found to be substantially large, methods of reducing vehicle emissions other than improvements in fuel efficiency need to be considered. Such solutions could include development of mass transit systems, bike lanes, sidewalks, and urban/social planning to reduce the need to commute.

### **3.4 CONCLUSIONS**

#### *3.4.1 SUMMARY*

Understanding the environmental impacts associated with usage of personal automobiles and how that impact changes over time is an important consideration when addressing key issues like human health and global climate change. Automobile usage consumes energy and resources while emitting pollutants that cause harm to humans and the environment. This study calculated the impact of personal vehicle usage across ten impact categories using NHTS data from study years 1990 and 1995 for the Milwaukee MSA and 2001 and 2009 for the state of Wisconsin. Data from an administered survey was also analyzed to calculate the impacts for the MMSA in 2016.

For Wisconsin as a whole, it was found that the impact per person decreased between 2001 and 2009 for seven of the eight pollutants, while energy use per person also decreased. This was paired with a nominal decrease in miles driven per person. The decrease in emissions was larger than the decrease in miles driven, indicating fuel economy improvements may be having a positive effect in reducing the impacts of transportation. This also illustrates the importance of

assessing more than only the rebound with respect to energy consumed, where environmental impact rebounds—such as the various emission pollutants calculated in this research—may determine a more robust depiction of the change in impacts associated with adoption of a fuel efficient vehicle.

The findings for the Milwaukee MSA were less positive. All eight pollutants increased between the two survey years while total water and total energy used also increased. An important factor that may have influenced this trend was the decrease in average fuel price between the survey years by \$0.19. This may help explain the increase in per person miles driven during this time, which in turn may have led to the increase in per person emissions. Differences in vehicle efficiency may also help account for the differences in results between the Milwaukee MSA and WI, considering the Milwaukee MSA data were 26 to 21 years antiquated while the Wisconsin data was within the last decade. The intervening years between the two data sets hosted improvements in fuel economy that may explain a portion of the temporal improvements. This pattern is supported with the MMSA impact data, where per person impacts were less than both the other two data sets for all but one impact category. Though improvements in vehicle technology may play a substantial role in reducing impacts, other factors such as availability and usage of alternate mode of transportation may have had an influence too.

It is also important to analyze the extent to which consumers change their driving behavior in response to adoption of more fuel efficient vehicles and whether they increase their consumption as efficiency increases, a dynamic known as the rebound effect. The data from the administered survey was used to calculate estimates of the rebound in the context of fuel consumption as well as for each of the ten impact categories. The respective fuel consumption and environmental impact rebounds for the general MMSA population were 206% and 213%. The environmental

impact rebound estimate for the rural and urban/suburban groups varied considerably with respective values of 30% and 260%, and the fuel consumption rebounds were -774% for the rural group and 337% for the urban/suburban groups. These rebound estimates differ with the bulk of the literature but are consistent with the estimate presented in Damhus (2014) (see section 1.0).

This general difference is largely due to varied methodology among the studies. Gillingham et al (2013) in *Nature* cites studies that determine the rebound to be small, indicating the rebound should not be used to hinder energy efficiency policies drastically. This differs from the findings in this study, where the rebound was found to be much larger. Based on their diminutive rebound, they posit that consumers are not apt to greatly increase their driving as fuel economy continues to improve, while the rebounds found in Dahmus (2014) and in this study suggest that improvements in vehicle fuel efficiency will lead to an increase in fuel consumed rather than a decrease. As a result of our findings, efficiency standards are not likely to achieve their aims of reducing fuel consumption and ultimately will not reduce the impact of air pollution imparted by personal automobiles.

### 3.4.2 LIMITATIONS

Limitations are often an inevitable consideration in any research. One set of constraints met with in this research was those innate to survey-based data. The respondent miles travelled data was a self-reported best estimate value and not an exact metric. The variability associated with using an estimate transgressed from the survey data to the general population via weighting factors and was existent in both the NHTS data and the survey administered in this study. A remedy for this limitation is difficult to realistically employ, short of using tracking technology to accurately measure miles travelled. Another limitation that increased variability was the incongruence

between the NHTS vehicle types and the vehicle types used in this study. As outlined in 3.3.3, this was overcome by corresponding NHTS vehicle types to the study vehicle types based on vehicle similarity and fuel efficiency.

When estimating the rebound with the administered survey data, the calculations were comprehensively dependent on participants' anticipated changes in driving behavior. Predicting how one may react to a given condition may unintentionally be considerably inaccurate. Similar to the miles travelled estimate limitation, this constraint could be alleviated with tracking technology, where miles driven data could be collected for participants before and after adoption of a more fuel efficient vehicle. This touches on another limitation of this study; the short duration of this study and the administered survey. Employing tracking technology would have required significantly more time than what was available for this study.

### *3.4.3 FUTURE STUDIES*

Additional research can be completed to account for some of the limitations discussed in 3.4.2. Obtaining data with vehicle tracking technology rather than survey data would be a productive method to further investigate the environmental impacts of personal transportation as well as drivers' tendencies to exhibit a rebound. On a more general scale, the impact and potential for rebound could be assessed for commercial transportation for systems like over-the-road trucking. This would probe the question of whether trucking activity increases with more fuel efficient trucks, whether that changes the impact of trucking, and if it shifts the environmental burden from one shipping sector to another (air plane, maritime shipping, etc.). Finally, a subsequent study could investigate the impact and rebound for other geographical locations as well as for the nation as a whole.

## **4.0 CONCLUSIONS**

### *4.1 SUMMARY AND CONTRIBUTIONS*

The rebound effect is an often overlooked consideration when examining attempts to reduce the environmental impact of transportation, particularly with respect to the use phase. When in the context of vehicle fuel efficiency improvements, the rebound effect describes the increase in miles driven associated with improvements in efficiency, and it depicts the percent of anticipated impact reduction given back due to the increase in consumption. This study analyzed survey data to investigate the following research topics: (1) the influence of changes in fuel price on consumer driving habits, (2) consumer vehicle purchasing motivations and preferences, (3) the environmental impact associated with personal transportation, (4) the change in impact over time, and (5) a calculated estimate of the magnitude of the rebound effect. Throughout the study, consumers were separated into groups based on type of geographical location of residence.

The results of the analyses indicated that there was no significant difference between the urban and suburban groups in the size of fuel price increase that would cause a change in driving behavior. At this shared price increase size, there did exist a difference in how each group would alter their driving tendencies. The urban group projected a larger increase in consumption of alternate modes of transportation when faced with the elevation in fuel price compared to the suburban group. The more widespread availability of alternate transportation in urban areas compared to suburban locations may offer an explanation for this result.

The assessment of consumers' impetuses for vehicle purchasing and valuation of vehicle attributes displayed a high degree of heterogeneity among consumers. No single attribute was identified as most important by a majority of respondents. Vehicle affordability boasted a plurality of 24% of participants ranking it most important, followed by 17% rating fuel economy

as most important, 11% of respondents valued vehicle reliability most highly, and 11% of participants voted vehicle performance as most important. By understanding that consumers vary widely in their determination of highly valued vehicle attributes, this knowledge can be implemented to aid adoption of fuel efficient vehicles. Aggregating multiple popular attributes with efficient fuel economy into a single vehicle may be a method of promoting widespread adoption of fuel efficient automobiles. This may facilitate consumers who do not necessarily value fuel efficiency to adopt a fuel efficient vehicle as a byproduct of pursuing other sought after vehicle attributes.

When utilizing the survey data to probe consumers' propensity to increase driving following adoption of a fuel efficient vehicle, it was found that 19% of the study participants predicted they would increase their annual number of miles driven in response to adoption of a vehicle with improved fuel economy. Within this portion of the population, a quarter of the participants anticipated increasing their driving activity significantly more (50% more miles), while the remaining 75% indicated they would slightly increase (25% more miles) their driving. An assessment of the change in miles driven after adoption for the entire surveyed population yielded a 9% increase in miles driven, which equated to 208,000 additional miles.

In addition to investigating consumer behavior, the environmental impact of driving was also studied. It was found that in Wisconsin as a whole, there was a decrease in total impacts in six impact categories and a decrease in per person impacts in eight impact categories between years 2001 and 2009. These trends coincide with increases in population and total miles driven during that time period, suggesting vehicle efficiency improvements may have played a role in reducing certain impacts. In the Milwaukee MSA between years 1990-1995, all ten impact categories exhibited an increase in impacts for both total impact and per person impact. This occurred while

population and miles driven also increased during this period, so it cannot be certain whether efficiency changes may have influenced the increase in impacts. With the data from the survey administered in this study, it was determined that per person impacts in the MMSA in 2016 were less than the per person impacts of drivers in Wisconsin as a whole across nine impact categories and was less than the Milwaukee MSA per person impacts across all ten studied impact categories. An important consideration in this comparison is the temporal differences among the data sets, where older data were likely associated with older, less fuel efficient vehicles.

With the environmental impact determined and the anticipated change in consumer driving behavior associated with adoption of a fuel efficient vehicle estimated, the rebound was investigated. Rebounds were calculated in the context of miles driven, fuel consumption, and environmental impact for the total population, rural group, and suburban/urban group. The miles driven rebound for the total population was 202%, 846% for the rural group, and 304% for the suburban/urban group. This indicates that the rate of change in miles driven for all three groups was larger than each group's respective rate of efficiency improvement, producing a backfire condition. The fuel consumption rebound was 206% for the total population, -774% for the rural group, and 377% for the suburban/urban group. The overall population and suburban/urban group showed conventional backfire, while participants in the rural group either decreased fuel consumed (reduced driving and/or increased efficiency) or decreased efficiency while increasing miles driven; the decrease in efficiency would produce a negative percent change in the rebound denominator, while the increase in miles driven would result in a positive percent change in the numerator, ultimately yielding a negative rebound. Lastly, the environmental impact rebound was found to be 213% for the total population, 30% for the rural group, and 260% for the suburban/urban group. This suggests that only the rural group generated a decrease in

environmental impact through adoption of a more efficient vehicle, whereas the overall population and the suburban/urban group increased their environmental impact. This introduces interesting consequences in the context of energy efficiency policy.

#### *4.2 ENERGY EFFICIENCY IMPLICATIONS*

With the overwhelming emphasis being placed on fuel economy improvements in the United States as the predominant method to reduce the environmental impact of transportation, it is important to understand how efficiency improvements will impact consumer driving behavior. The rebound is particularly relevant, as it helps describe the efficacy level of fuel economy mandates; small rebounds suggest high efficacy through little increase in driving and a decrease in environmental impact, while large rebounds outline low efficacy with sizeable increases in driving and minimal or increased environmental impact.

The findings of large, backfire-condition rebounds in this study indicate that fuel economy standards may not be a viable method to reduce the impact of transportation. The large rebounds portend to an increase in both fuel consumed and environmental impact, which fails to achieve the goal of fuel economy standards of reducing fuel consumption. Based on the results of this research, legislative bodies may be best served abandoning their push to improve vehicle fuel efficiency and put more focus on other methods to reduce fuel consumption. It should be recalled, however, that the methodology used in this research differed from that of other studies—which calculated the rebound to be around 20%—where this research did not include various econometric factors. This research employed its methodology, which reflected that used in Dahmus (2014), based on its ease of use and flexibility in application.

An alternate area to investigate for reducing transportation impacts is a tax-based approach. This could be in the form of a fuel tax and/or a tax on fuel inefficient vehicles. The premise behind both taxes is to artificially increase the price of those goods to reduce demand and consumption of them; a fuel tax would likely lead to reduced fuel usage, while an inefficient vehicle tax would create disincentives for consumers to adopt those vehicles, likely pushing them towards more fuel efficient vehicles. The latter option of moving towards fuel efficient automobiles, however, returns the rebound propensity into consideration, indicating a fuel tax may be the better option. Further study is needed to substantiate this concept.

When assessing the sustainability of a good or service, it is important to consider all three factions of sustainability: environmental, economic, and social. While this research focuses predominantly on the environmental consideration of sustainability for transportation in the context of environmental impact, there are myriad social benefits that arrive from transportation that bear mentioning. The ability to travel longer distances in a relatively short amount of time allows people to commute to work, the grocery store, and sundry other places. The advent of the automobile and modern road transportation has also allowed goods to be transported across the country, creating strong economic growth while providing consumers with many otherwise unattainable goods. These social benefits derived from modern vehicular transportation allow modern developed society to function in its current interconnected manner that has become so depended upon. The environmental impacts analyzed in this study are coincident with these benefits, and it is advantageous to understand this tradeoff when assessing the topic of vehicle sustainability.

#### *4.3 FUTURE WORK*

The findings in this study provide useful insight into consumer driving behavior and the implications of energy efficiency advancements. As is the case with most research, future work can build on these findings to further investigate the topic and expand the breadth of the work. Subsequent studies could enlarge the study area and capture data from larger sample sizes. Concurrently, a higher resolution could be used to quantify the anticipated change in driving following adoption, augmenting the 25% increase and 50% increase options to include additional options with smaller intervals, such as 10%, 20%, 30%, etc. increases, though this may be difficult for consumers to conceptualize. Allowing for participants to express more heterogeneity in their predicted behavior changes may be expected to increase the accuracy of the results. Expanding the geographical region of study and examining additional locations could allow for comparisons to be made among different metropolitan areas, states, or regions.

Moving beyond the methodology applied in this study, future works could employ a more tailored and metric-based approach to collecting consumer driving data rather than relying on survey responses where consumers attempt to predict their future behavior. One such method could be to utilize tracking technology to measure driving data prior to and post adoption of a fuel efficient vehicle. This could largely remedy the inherent inaccuracies of consumers attempting to predict their future behavior. A study using tracking methods would require a longer duration and additional resources. The execution of these future studies could help construct a more comprehensive understanding of personal transportation energy consumption, ultimately allowing for adequate regulation of fuel consumption and the corresponding environmental impact. The enactment of a suitable regulatory structure can have a significant influence in mitigating the environmental impact of personal transportation and will be a strong positive step in combating anthropogenic climate change and environmental degradation.

Another avenue for future study lays in identifying potential future policies and studying the sustainability implications. Possible future policies may encompass mandates for alternate vehicle fuel sources such as biofuels or electric vehicles, innovative battery technology, and energy generation and storage. Each of these conceivable policies should be analyzed with respect to their consequences for sustainability. Similar considerations to those assessed in this study could be applied, such as modelling the propensity to rebound and the extent to which environmental impacts may change as a result. The findings of such analyses may not only provide insight into the likelihood that each strategy may lead to an overall net reduction in impacts, but it may help reveal which combination of policies may optimize sustainability. Studies investigating these various research pathways can be a suitable step towards ultimately transitioning the transportation network into a sustainable sector by reducing the environmental impacts while maintaining or expanding the benefits provided by vehicle travel.

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## **APPENDIX**

### **1. Survey Vehicle**

Consent.

UNIVERSITY OF WISCONSIN-MADISON

Research Participant Information and Consent Form

Title of the Study: Environmental implications of efficiency: fuel efficient vehicles and the rebound effect

Principal Investigator: Dr. Andrea Hicks (phone: 608.262.1262) (email: hicks5@wisc.edu)

Student Researcher: James Mahoney (email: jmmahoney2@wisc.edu)

#### **DESCRIPTION OF THE RESEARCH**

You are invited to participate in a research study about the extent to which consumer driving habits change in response to improved vehicle fuel efficiency. More specifically, the research investigates whether consumers drive more when they adopt a vehicle with improved fuel efficiency when compared to their previous vehicle.

You have been invited to participate because you own a vehicle, reside in the Madison Metropolitan Statistical Area, and are 18 years old or older.

The purpose of the research is to investigate whether improved vehicle fuel efficiency results in an increase in miles driven, which can be used to suggest whether legislation mandating stricter fuel economy standards will successfully reduce emissions.

This study will include residents of the Madison Metropolitan Statistical Area who own at least one motor vehicle and are 18 years of age or older.

This research will be conducted via a consumer survey advertised on Madison Craigslist on the internet and administered through Qualtrics.

#### **WHAT WILL MY PARTICIPATION INVOLVE?**

If you decide to participate in this research, you will be asked to complete a consumer survey that gathers information on your driving habits, motivations for purchasing a vehicle, and demographic data.

You will be asked to complete 1 survey.

Your participation will last approximately 10 minutes per session and will require 1 session.

ARE THERE ANY RISKS TO ME?

The only anticipated risk is the potential for a breach of confidentiality associated with the collection of participants' email addresses and names.

ARE THERE ANY BENEFITS TO ME?

There are no direct benefits.

WILL I BE COMPENSATED FOR MY PARTICIPATION?

You will receive a \$5 Amazon.com digital gift certificate for participating in this study. The gift certificate will be sent to the participant when the survey has reached capacity and is closed, rather than when the participant completes the survey.

If you do withdraw prior to the end of the study, there will be no penalty and you will not receive the participation reward. You will also not receive the reward if you indicate you would prefer not to be contacted.

HOW WILL MY CONFIDENTIALITY BE PROTECTED?

A breach of confidentiality will be protected against by storing the data in a password secured location. Results will only be disseminated in anonymized or aggregate form.

WHOM SHOULD I CONTACT IF I HAVE QUESTIONS?

You may ask any questions about the research at any time. If you have questions about the research after you leave today you should contact the Principal Investigator Dr. Andrea Hicks at 608.262.1262 or email (hicks5@wisc.edu). You may also email the student researcher, James Mahoney, at jmmahoney2@wisc.edu.

If you are not satisfied with response of research team, have more questions, or want to talk with someone about your rights as a research participant, you should contact the Education and Social/Behavioral Science IRB Office at 608-263-2320.

Your participation is completely voluntary. If you decide not to participate or to withdraw from the study it will have no effect on any services or treatment you are currently receiving.

A copy for records will be provided upon request.

Upon completion of the survey, you will have the option to accept the participation reward. To accept and receive the reward, you will need to provide your name and email address.

*By selecting "Yes" I acknowledge I have read this consent form, had an opportunity to ask any questions about my participation in this research, and voluntarily consent to participate.*

- Yes
- No

Q1. How many vehicles are in your household?

- 0
- 1
- 2
- 3
- 4
- Other:

Q2. How many drivers live in your household?

- 0
- 1
- 2
- 3
- 4
- Other:

Q3. In what type of geographical region do you live?

- Rural
- Suburban
- Urban

Q4. Please select the zip code in which you live:

Q5. What is the total number of miles driven by all drivers in your household per year?

- 0 to 5,000 miles

- 5,000 to 10,000 miles
- 10,000 to 15,000 miles
- 15,000 to 20,000 miles
- 20,000 to 35,000 miles
- 35,000 to 60,000 miles
- 60,000 to 100,000 miles
- 100,000 to 150,000 miles
- 150,000+ miles

Q6. Which destinations do you most often drive your vehicle to and how frequently? (Example of destination entry: "Home to work."  
Please work on a round-trip basis, where "home to work" is the same as "work to home.")

Destination 1	<input type="text"/>	<input type="radio"/> Fewer than 1 time per month	<input type="radio"/> 1 to 4 times per month	<input type="radio"/> 1 time per week	<input type="radio"/> 1 to 4 times per week	<input type="radio"/> 5+ times per week
Destination 2	<input type="text"/>	<input type="radio"/> Fewer than 1 time per month	<input type="radio"/> 1 to 4 times per month	<input type="radio"/> 1 time per week	<input type="radio"/> 1 to 4 times per week	<input type="radio"/> 5+ times per week
Destination 3	<input type="text"/>	<input type="radio"/> Fewer than 1 time per month	<input type="radio"/> 1 to 4 times per month	<input type="radio"/> 1 time per week	<input type="radio"/> 1 to 4 times per week	<input type="radio"/> 5+ times per week
Destination 4	<input type="text"/>	<input type="radio"/> Fewer than 1 time per month	<input type="radio"/> 1 to 4 times per month	<input type="radio"/> 1 time per week	<input type="radio"/> 1 to 4 times per week	<input type="radio"/> 5+ times per week
Destination 5	<input type="text"/>	<input type="radio"/> Fewer than 1 time per month	<input type="radio"/> 1 to 4 times per month	<input type="radio"/> 1 time per week	<input type="radio"/> 1 to 4 times per week	<input type="radio"/> 5+ times per week
Destination 6	<input type="text"/>	<input type="radio"/> Fewer than 1 time per month	<input type="radio"/> 1 to 4 times per month	<input type="radio"/> 1 time per week	<input type="radio"/> 1 to 4 times per week	<input type="radio"/> 5+ times per week
Destination 7	<input type="text"/>	<input type="radio"/> Fewer than 1 time per month	<input type="radio"/> 1 to 4 times per month	<input checked="" type="radio"/> 1 time per week	<input type="radio"/> 1 to 4 times per week	<input type="radio"/> 5+ times per week
Destination 8	<input type="text"/>	<input type="radio"/> Fewer than 1 time per month	<input type="radio"/> 1 to 4 times per month	<input type="radio"/> 1 time per week	<input type="radio"/> 1 to 4 times per week	<input type="radio"/> 5+ times per week
Destination 9	<input type="text"/>	<input type="radio"/> Fewer than 1 time per month	<input type="radio"/> 1 to 4 times per month	<input type="radio"/> 1 time per week	<input type="radio"/> 1 to 4 times per week	<input type="radio"/> 5+ times per week
Destination 10	<input type="text"/>	<input type="radio"/> Fewer than 1 time per month	<input type="radio"/> 1 to 4 times per month	<input type="radio"/> 1 time per week	<input type="radio"/> 1 to 4 times per week	<input type="radio"/> 5+ times per week

Q7. How often do you use an alternative mode of transportation?

- Never
- 1 to 4 times per month
- 1 time per week
- 1 to 4 times per week
- 5+ times per week

Q8. What type alternative transportation do you use? (Please check all that apply.)

- None
- Walk
- Bicycle
- Bus
- Carpool
- Other:

Q9. What type(s) of vehicle(s) do you currently own in your household? (Please select "No vehicle" for vehicle numbers beyond that which you own. For example, if your household has three vehicles, please select "No vehicle" for vehicles four-six.)

Vehicle 1	<input type="radio"/> No vehicle	<input type="radio"/> Large pickup truck	<input type="radio"/> Small pickup truck	<input type="radio"/> SUV	<input type="radio"/> Hybrid SUV	<input type="radio"/> Large sedan	<input type="radio"/> Small sedan	<input type="radio"/> Hybrid sedan	<input type="radio"/> Coupe (two door)	<input type="radio"/> Other
Vehicle 2	<input type="radio"/> No vehicle	<input type="radio"/> Large pickup truck	<input type="radio"/> Small pickup truck	<input type="radio"/> SUV	<input type="radio"/> Hybrid SUV	<input type="radio"/> Large sedan	<input type="radio"/> Small sedan	<input type="radio"/> Hybrid sedan	<input type="radio"/> Coupe (two door)	<input type="radio"/> Other
Vehicle 3	<input type="radio"/> No vehicle	<input type="radio"/> Large pickup truck	<input type="radio"/> Small pickup truck	<input type="radio"/> SUV	<input type="radio"/> Hybrid SUV	<input type="radio"/> Large sedan	<input type="radio"/> Small sedan	<input type="radio"/> Hybrid sedan	<input type="radio"/> Coupe (two door)	<input type="radio"/> Other
Vehicle 4	<input type="radio"/> No vehicle	<input type="radio"/> Large pickup truck	<input type="radio"/> Small pickup truck	<input type="radio"/> SUV	<input type="radio"/> Hybrid SUV	<input type="radio"/> Large sedan	<input type="radio"/> Small sedan	<input type="radio"/> Hybrid sedan	<input type="radio"/> Coupe (two door)	<input type="radio"/> Other
Vehicle 5	<input checked="" type="radio"/> No vehicle	<input type="radio"/> Large pickup truck	<input type="radio"/> Small pickup truck	<input type="radio"/> SUV	<input type="radio"/> Hybrid SUV	<input type="radio"/> Large sedan	<input type="radio"/> Small sedan	<input type="radio"/> Hybrid sedan	<input type="radio"/> Coupe (two door)	<input type="radio"/> Other
Vehicle 6	<input type="radio"/> No vehicle	<input type="radio"/> Large pickup truck	<input type="radio"/> Small pickup truck	<input type="radio"/> SUV	<input type="radio"/> Hybrid SUV	<input type="radio"/> Large sedan	<input type="radio"/> Small sedan	<input type="radio"/> Hybrid sedan	<input type="radio"/> Coupe (two door)	<input type="radio"/> Other

Q10. What is the model year of each vehicle in your household? (Please select "No vehicle" for vehicle numbers beyond that which you own. For example, if your household has three vehicles, please select "No vehicle" for vehicles four-six.)

Vehicle 1	<input type="radio"/> No vehicle	<input type="radio"/> Earlier than 1980	<input type="radio"/> 1980-1989	<input type="radio"/> 1990-1999	<input type="radio"/> 2000-2004	<input type="radio"/> 2005-2009	<input type="radio"/> 2010-2014	<input type="radio"/> 2015-2016
Vehicle 2	<input type="radio"/> No vehicle	<input type="radio"/> Earlier than 1980	<input type="radio"/> 1980-1989	<input type="radio"/> 1990-1999	<input type="radio"/> 2000-2004	<input type="radio"/> 2005-2009	<input type="radio"/> 2010-2014	<input type="radio"/> 2015-2016
Vehicle 3	<input type="radio"/> No vehicle	<input type="radio"/> Earlier than 1980	<input type="radio"/> 1980-1989	<input type="radio"/> 1990-1999	<input type="radio"/> 2000-2004	<input type="radio"/> 2005-2009	<input type="radio"/> 2010-2014	<input type="radio"/> 2015-2016
Vehicle 4	<input type="radio"/> No vehicle	<input type="radio"/> Earlier than 1980	<input type="radio"/> 1980-1989	<input type="radio"/> 1990-1999	<input type="radio"/> 2000-2004	<input type="radio"/> 2005-2009	<input type="radio"/> 2010-2014	<input type="radio"/> 2015-2016
Vehicle 5	<input type="radio"/> No vehicle	<input type="radio"/> Earlier than 1980	<input type="radio"/> 1980-1989	<input type="radio"/> 1990-1999	<input type="radio"/> 2000-2004	<input type="radio"/> 2005-2009	<input type="radio"/> 2010-2014	<input type="radio"/> 2015-2016
Vehicle 6	<input type="radio"/> No vehicle	<input type="radio"/> Earlier than 1980	<input type="radio"/> 1980-1989	<input type="radio"/> 1990-1999	<input type="radio"/> 2000-2004	<input type="radio"/> 2005-2009	<input type="radio"/> 2010-2014	<input type="radio"/> 2015-2016

Q11. How many miles per week are each of the vehicles in your household driven? Please provide your best estimate. (Please select "No vehicle" for vehicle numbers beyond that which you own. For example, if your household has three vehicles, please select "No vehicle" for vehicles four-six.)

Vehicle 1	<input type="radio"/> No vehicle	<input checked="" type="radio"/> 1-24	<input type="radio"/> 25-49	<input type="radio"/> 50-99	<input type="radio"/> 100-149	<input type="radio"/> 150-199	<input type="radio"/> 200-249	<input type="radio"/> 250+
Vehicle 2	<input type="radio"/> No vehicle	<input type="radio"/> 1-24	<input type="radio"/> 25-49	<input type="radio"/> 50-99	<input type="radio"/> 100-149	<input type="radio"/> 150-199	<input type="radio"/> 200-249	<input type="radio"/> 250+
Vehicle 3	<input type="radio"/> No vehicle	<input type="radio"/> 1-24	<input type="radio"/> 25-49	<input type="radio"/> 50-99	<input type="radio"/> 100-149	<input type="radio"/> 150-199	<input type="radio"/> 200-249	<input type="radio"/> 250+
Vehicle 4	<input type="radio"/> No vehicle	<input type="radio"/> 1-24	<input type="radio"/> 25-49	<input type="radio"/> 50-99	<input type="radio"/> 100-149	<input type="radio"/> 150-199	<input type="radio"/> 200-249	<input type="radio"/> 250+

Vehicle 5

- No vehicle
- 1-24
- 25-49
- 50-99
- 100-149
- 150-199
- 200-249
- 250+

Vehicle 6

- No vehicle
- 1-24
- 25-49
- 50-99
- 100-149
- 150-199
- 200-249
- 250+

Q12. How many times do you fill up the gasoline tank of each vehicle in your household per month? (Please select "No vehicle" for vehicle numbers beyond that which you own. For example, if your household has three vehicles, please select "No vehicle" for vehicles four-six.)

Vehicle 1	<input type="radio"/> No vehicle	<input type="radio"/> 1	<input type="radio"/> 2	<input type="radio"/> 3	<input type="radio"/> 4	<input type="radio"/> 5	<input type="radio"/> 6+
Vehicle 2	<input type="radio"/> No vehicle	<input type="radio"/> 1	<input type="radio"/> 2	<input type="radio"/> 3	<input type="radio"/> 4	<input type="radio"/> 5	<input type="radio"/> 6+
Vehicle 3	<input type="radio"/> No vehicle	<input type="radio"/> 1	<input type="radio"/> 2	<input type="radio"/> 3	<input type="radio"/> 4	<input type="radio"/> 5	<input type="radio"/> 6+
Vehicle 4	<input checked="" type="radio"/>	<input type="radio"/> 1	<input type="radio"/> 2	<input type="radio"/> 3	<input type="radio"/> 4	<input type="radio"/> 5	<input type="radio"/> 6+
Vehicle 5	<input type="radio"/> No vehicle	<input type="radio"/> 1	<input type="radio"/> 2	<input type="radio"/> 3	<input type="radio"/> 4	<input type="radio"/> 5	<input type="radio"/> 6+
Vehicle 6	<input type="radio"/> No vehicle	<input type="radio"/> 1	<input type="radio"/> 2	<input type="radio"/> 3	<input type="radio"/> 4	<input type="radio"/> 5	<input type="radio"/> 6+

Q13. At which gasoline price increase amount would you change your driving habits?

- No price increase would change my driving habits
- \$0.50/gal
- \$1.00/gal
- \$1.50/gal
- \$2.00/gal
- \$3.00/gal
- \$4.00/gal

Q14. At the gasoline price increase you selected in question 13, how would you change your driving habits? (Please check all that apply.)

I would:

- Drive significantly more miles (50% more)
- Drive slightly more miles (25% more)
- Drive slightly fewer miles (25% fewer)
- Drive significantly fewer miles (50% fewer)
- Carpool trips more often
- Combine trips more often
- Use alternative modes of transportation (i.e. bus, bicycle, walk, etc.)
- Not change my driving habits

Q15. Please rank the following vehicle attributes from 1 (most important to you) to 15 (least important to you). Please click and hold on each attribute and drag it to the desired ranking location.

- Fast acceleration
- Luxury amenities
- Brand loyalty
- Efficient fuel economy (35 mpg)
- "Greenness"
- Influence of others
- High performance rating
- High power rating
- Price/affordability
- High reliability rating
- High safety rating
- Large size

- Sporty style
- Cargo space
- Passenger seating capacity

Q16. In how many years from now do you plan on buying another vehicle?

- I have no plans to buy another vehicle
- 0-1 years
- 1-3 years
- 3-5 years
- 5+ years

Q17. What type of vehicle do you plan on purchasing?

- Large pickup truck
- Small pickup truck
- SUV
- Hybrid SUV
- Large sedan
- Small sedan
- Hybrid sedan
- Other:

Q18. Will this vehicle be new or used?

- New
- Used

Q19. Will this vehicle replace a current vehicle of yours or be an addition to the number of vehicles in your household?

- Replace a current vehicle
- Addition to the number of vehicles currently owned

Q21. If you saved money on fuel by purchasing a more fuel efficient vehicle, what would you do with the money you saved on fuel?

- Drive more
- Travel (via non-automobile transportation, such as flying, train, etc.)
- Go out to eat more often
- Buy more clothes, books, and other consumer goods
- Donate to a charity
- Deposit it in a bank account or invest it
- Other:

Q22. Would increased future fuel prices have any effect on what vehicle you plan to purchase?

- Yes. (Please explain briefly.)
- No. (Please explain briefly.)

Q23. Please specify your age.

- Under 20 years old
- 20-29 years old
- 30-39 years old
- 40-49 years old
- 50-59 years old
- 60-69 years old
- 70+ years old

Q24. Please specify your gender.

- Male
- Female

Q25. Please specify your ethnicity.

- Hispanic
- Non-Hispanic
- Unknown

Q26. Please specify your race.

- Asian/Pacific Islander
- Black or African American
- Native American
- White
- Other
- Unknown

Q27. Please specify your marital status.

- Single, never married
- Married or domestic partnership
- Separated
- Divorced
- Widowed

Q28. Please specify the highest level of education you have completed.

- No schooling completed
- Up to 8th grade
- Some high school
- High school diploma or equivalent
- Some college
- Associate's degree
- Bachelor's degree
- Master's degree
- Professional degree
- Doctorate degree

Q29. Please specify your living situation.

- Own a house
- Rent a house
- Own an apartment or condominium
- Rent an apartment or condominium

Other:

Q30. Please specify your annual household income level before taxes.

- Less than \$25,000
- \$25,000 to \$34,999
- \$35,000 to \$49,999
- \$50,000 to \$74,999
- \$75,000 to \$99,999
- \$100,000 to \$149,999
- \$150,000 to \$199,999
- \$200,000 or more

Q31. Thank you for your participation. Please specify whether you would like to receive the \$5 Amazon.com digital gift certificate for participating in the survey? If yes, please enter an email address at which you would like to receive the gift code. By selecting "Yes" and entering an email address, you hereby consent to be contacted by the survey administrator for the purpose of receiving the gift code.

- Yes
- No

## 2. Aggregate Survey Data

Q1. How many vehicles are in your household?

**Table S1** Aggregate survey responses for Q1

Number of Vehicles in the Household	% of Respondents
0	0%
1	50%
2	38%
3	11%
4	1%

**Table S2** Statistical data for Q1

#	Answer	Bar	Response	%
1	0	0	0	0%
2	1	0.5	99	50%
3	2	0.383838384	76	38%
4	3	0.106060606	21	11%
5	4	0.01010101	2	1%
6	Other:	0	0	0%
Total			198	100%

**Table S3** Statistical data for Q1

Statistic	Value
Min Value	2
Max Value	5
Mean	2.63
Variance	0.51
Standard Deviation	0.71
Total Responses	198

Q2. How many drivers live in your household?

**Table S4** Aggregate survey responses for Q2

Number of drivers in household	% of respondents
0	1%
1	32%
2	58%
3	8%
4	1%

**Table S5** Statistical data for Q2

#	Answer	Bar	Response	%
1	0	0.01010101	2	1%
2	1	0.318181818	63	32%
3	2	0.580808081	115	58%
4	3	0.080808081	16	8%
5	4	0.01010101	2	1%
6	Other:	0	0	0%
Total			198	100%

**Table S6** Statistical data for Q2

Statistic	Value
Min Value	1
Max Value	5
Mean	2.76
Variance	0.43
Standard Deviation	0.65
Total Responses	198

Q3. In what type of geographical region do you live?

**Table S7** Aggregate survey responses for Q3

Geographical region of residence	% of respondents
Rural	12%
Suburban	39%
Urban	49%

**Table S8** Statistical data for Q3

#	Answer	Bar	Response	%
1	Rural	0.116162	23	12%
2	Suburban	0.393939	78	39%
3	Urban	0.489899	97	49%
	Total		198	100%

**Table S9** Statistical data for Q3

Statistic	Value
Min Value	1
Max Value	3
Mean	2.37
Variance	0.47
Standard Deviation	0.68
Total Responses	198

Q4. Please select the zip code in which you live:

**Table S10** Aggregate survey responses for Q4

Zip Codes of Participants						
20002	50322	52801	53590	53704	53711	53716
20002	50401	52804	53590	53704	53713	53716
20005	50511	53507	53590	53704	53713	53716
20005	50515	53508	53590	53704	53713	53716
20005	50530	53508	53590	53704	53713	53717
20005	50601	53508	53590	53704	53713	53717
20007	50653	53526	53590	53704	53713	53717
20017	50660	53526	53590	53705	53713	53718
20036	50677	53528	53590	53705	53713	53718
20783	50836	53529	53593	53705	53713	53718
20904	50836	53529	53593	53705	53714	53719
50001	51053	53531	53597	53705	53714	53719
50001	51101	53533	53597	53706	53714	53719
50001	51101	53535	53597	53706	53714	53719
50028	51101	53555	53597	53711	53714	53726
50056	51351	53555	53703	53711	53714	53901
50103	51638	53558	53703	53711	53715	53901
50254	51647	53562	53703	53711	53715	53913
50263	52001	53562	53703	53711	53715	53954
50266	52043	53562	53703	53711	53715	53959
50266	52043	53562	53703	53711	53715	55049
50266	52043	53573	53703	53711	53715	55379
50273	52217	53575	53703	53711	53715	55931
50309	52537	53575	53703	53711	53716	55931
50309	52632	53589	53703	53711	53716	90017
50309	52637	53589	53703	53711	53716	111611
50309	52748	53590	53703	53711	53716	111611
50322	52761	53590	53704	53711	53716	111611

Q5. What is the total number of miles driven by all drivers in your household per year?

**Table S11** Aggregate survey responses for Q5

Total miles driven by all drivers in household	% of respondents
0 - 5,000	4%
5,000 - 10,000	16%
10,000 - 15,000	18%
15,000 - 20,000	32%
20,000 - 35,000	20%
35,000 - 60,000	9%
60,000 - 100,000	2%
100,000 - 150,000	1%
150,000+	0%

**Table S12** Statistical data for Q5

#	Answer	Bar	Response	%
1	0 to 5,000 miles	0.035354	7	4%
2	5,000 to 10,000 miles	0.161616	32	16%
3	10,000 to 15,000 miles	0.176768	35	18%
4	15,000 to 20,000 miles	0.318182	63	32%
5	20,000 to 35,000 miles	0.20202	40	20%
6	35,000 to 60,000 miles	0.085859	17	9%
7	60,000 to 100,000 miles	0.015152	3	2%
8	100,000 to 150,000 miles	0.005051	1	1%
9	150,000+ miles	0	0	0%
	Total		198	100%

**Table S13** Statistical data for Q5

Statistic	Value
Min Value	1
Max Value	8
Mean	3.83
Variance	1.89
Standard Deviation	1.37
Total Responses	198

Q6. Which destinations do you most often drive your vehicle to and how frequently? (Example of destination entry: "Home to work." Please work on a round-trip basis, where "home to work" is the same as "work to home.")

**Table S14** Aggregate survey responses for Q6

#	Question	Fewer than 1 time per month	1 to 4 times per month	1 time per week	1 to 4 times per week	5+ times per week	Total Responses	Mean
1	Destination 1	1	11	12	52	122	198	4.43
2	Destination 2	75	28	28	44	23	198	2.56
3	Destination 3	108	26	19	37	8	198	2.05
4	Destination 4	137	26	11	21	3	198	1.62
5	Destination 5	150	21	9	14	4	198	1.49
6	Destination 6	149	29	7	11	2	198	1.42
7	Destination 7	149	27	8	12	2	198	1.44
8	Destination 8	154	20	12	9	3	198	1.42
9	Destination 9	160	25	5	5	3	198	1.31
10	Destination 10	156	22	10	7	3	198	1.38

**Table S15** Statistical data for Q6

<b>Statistic</b>	<b>Destination 1</b>	<b>Destination 2</b>	<b>Destination 3</b>	<b>Destination 4</b>	<b>Destination 5</b>	<b>Destination 6</b>	<b>Destination 7</b>	<b>Destination 8</b>	<b>Destination 9</b>	<b>Destination 10</b>
Min Value	1	1	1	1	1	1	1	1	1	1
Max Value	5	5	5	5	5	5	5	5	5	5
Mean	4.43	2.56	2.05	1.62	1.49	1.42	1.44	1.42	1.31	1.38
Variance	0.76	2.16	1.76	1.17	1.01	0.77	0.82	0.82	0.6	0.73
Standard Deviation	0.87	1.47	1.33	1.08	1.01	0.88	0.9	0.91	0.78	0.86
Total Responses	198	198	198	198	198	198	198	198	198	198

Destination 1	Destination 2	Destination 3	Destination 4	Destination 5	Destination 6	Destination 7	Destination 8	Destination 9	Destination 10
QID6-1-TEXT	QID6-2-TEXT	QID6-3-TEXT	QID6-4-TEXT	QID6-5-TEXT	QID6-6-TEXT	QID6-7-TEXT	QID6-8-TEXT	QID6-9-TEXT	QID6-10-TEXT
6-1	6-2	6-3	6-4	6-5	6-6	6-7	6-8	6-9	6-10
5 home to work	3 home to grocery store	1 home to movie	1 home to family town	1 home to pharmacy	1 home to coffee shop	3 home to sports	4 home to gym	3 work to restaurant	1 home to restaurant
4 School	2 Dubuque, Ia	4 Downtown Reedsburg	4 Wisconsin Dells	4 Daughter LaValle, WI	2 Hospital, Reedsburg	2 Wal-Mart Baraboo	4 Rides	4 Breakfast	3 Ho Chunk Casino
5 home to work	3 home to church	3 home to grocery store	4 other	3 other	4 other	3 other	4 other	3 other	4 other
5 Home to work	3 Home to grocery stores	4 Home to entertainment	1 Home to airport	2 Home to other shopping	2 Home to Chicago	4 Home to restaurant	3 Home to UW Madison	1 Home to Wisconsin Dells	2 Home to medical/dental/pharmacy
5 home to school	4 grocery shopping	3 family	4 errands	3 home to doctors	5 home to work	4 home to daycare	3 clothes shopping	4 home to friend	3 home to restaurant

5	Home to work	5	Home to mall	4	Home to restaurant	3	Home to other office	2	Home to relatives	2	Home to church	3	Home to friends	5	Home to daycare	5	Home to gym	5	Home to grocery store
4	home to work	5	Daycare	4	home to school	2	Shopping	1	movies	1	out of town	1	laundry	1		1		1	
5	Home to work	5	Work to daycare	4	Home to stores	1		1		1		1		1		1		1	
4	work	5	work	4	restaurant	3	church	5	school	2	friends house	1	relative's house	4	food store	2	clothing store	2	drug store
2	Home to Volunteer	2	Home to Shop	1		1		1		1		1		1		1		1	
5	home to work	3	home to grocery store	1	home to family home (IL)	1	home to movie theater	1	home to pharmacy	1	home to family home (MI)	1	home to park	1	home to friends' home	1	home to spouse's work location	1	home to auto repair shop
3	grocery	3	errands	4	coaching	4	yoga	2	other	1	nul	1	nul	1	nul	1	nul	1	nul

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2	other errands/shopping	2	restaurant/bar	2	recreational destination/park	1	road trip/vacation	1	medical appointments	1	hardware store	1	public meetings	1	movies, plays, concerts	1	visit friends	1	business meetings
4	Dog Park	2	Grocery	1	Doctor	1	Music venue	1	restaurant	1	n/a	1	n/a	1	n/a	1	n/a	1	n/a
4	home to roller derby	3	home to Humane Society	2	home to woodmans	1	home to chic ago	1	home to work	1	home to trade r joes	2	home to friends house	1	home to mil waukee	1	home to mall	1	home to arboretum
3	Home to shopping	4	Home to dog park	1	Home to visit family out of town	1	Vacation about 4 hours roundtrip	1		1		1		1			1		
3	Home to Mall	2	Home to Movie	4	Home to Church	4	Home to Woo	4	Home to Sun Prarie	3	Home to Coppers	3	Home to School	5	Home to Gas station	2	Home to Bar	1	Home to Club

			Theater				dmas												
4	Home to work	4	Grocery store	3	best friend's house	2	mother's house	2	to boyfriend's parents' house	2	clothing shopping	3	Dig N' Save	2	Mechanic's Shop	2	the Cardinal Bar	4	Walgreens
5	home to work	2	home to Menards	1	home to Neosho	4	home to boyfriend	3	home to grocer	1	home to Costco	1	Home to Milwaukee	1	home to coop	1	Home to Mnpls	1	Home to Chicago
5	Home to work	4	Home to friend's house	3	Home to grocery	2	Home to downtown	1	Home to airport	1	Work travel	1	Home to mall	2	Home to restaurant	1	Home to Milwaukee	1	Home to Chicago
5	Home to work	3	Home to kids school	2	Home to 4H	4	Work to grocery store	1	Home to aunts house	1	Home to volunteer meeting	2	Home to stores	2	Home to restaurants	1	Home to camping	1	Home to vacation/outings

4	Home to various stores for shopping	3	Home to social engagements, mtgs	2	Home to visit out of state family	1	Home to Medical appts	1		1		1		1		1			
5	home to work	4	home to Madison to shop	2	Dubuque	1	Chicago	2	Milwaukee	4	Madison, eat or entertainment	2	Firchburg, in laws	2	Blue Mounds	2	Baraboo/Dells	2	Sauk City
5	Home to Work	3	Home to Groceries	3	Home to Department Store	4	Home to Gym	3	Home to Downtown	1	Home to Chicago	1	Home to Milwaukee	1	Home to Fox Cities	1	Home to Kansas City	2	Home to Park
5	Work to home	4	Home to gym	2	Home to grocery store	1	Home to Rockford, IL	1	Home to Chicago	3	Home to friend's house	2	Home to thrift store	2	Home to Plasma Bank	2	Home to second job	3	Home to library
5	Home to work	4	Home to church	3	Home to grocery store	3	Home to gas station	1	Home to Missouri	2	Home to Madison	2	Home to adams	2	Home to Reedsburg	5	Home to wife's work	2	Home to car wash

5	home to work	3	volunteer mtg	1		1		1		1		1		1		1			
5	Home to parents	5	Home to work	1		1		1		1		1		1		1			
5	Home to work	4	Home to church	2	Home to client meeting or photo shoot	3	Home to grocery store	4	Home to misc errands	2	Home to falls river wi	1	Home to muscod a	1	Home to watertown	1	Home to milwaukee	2	Home to stoughton
5	home to work	3	week end errands	4	Dinner out	1	Out of town	1		1		1		1		1			
3	home to work	3	grocery store from home	3	errands	2	gas	1	visits	1	car maintenance	1	Medical	1	dry cleaning pick up	1	recreation	1	entertainment
5	Home to Work	4	Home to Downtown Madison	1	Home to Chicago	1	Home to Minneapolis	1	Home to Milwaukee	3	Home to grocery store	2	Home to doctor appointments	3	Home to restaurants	1	Home to shopping mall	1	Home to other misc

4	home to grocery store	3	home to gas station	4	home to post office	3	home to restaurant	1	home to department store	1	home to mall	2	home to fast food restaurant	1	home to park	2	home to ups store	2	home to fedex office store
5	Home to work	5	Home to gym	4	home to grocery store	4	Home to aa meeting	2	home to dads house	2	home to dr	2	aa to gym	2	home to julias house	2	julias house to aa	2	home to gas station
4	Home to Work	4	Home to Grocery Store	1	Home to Racine	1	Home to Door County	1	Home to Columbus, Wi	3	Home to Church	2	Home to Coffee Shop	1	Home to Doctor's Office	2	Home to Stoughton	2	Home to Movie Theater
4	work	4	friend	3	grocery store	4	boyfriend	2	library	1		1		1		1		1	
5	GasPrices	2	Sauk City	3	General shopping	1		1		1		1		1		1		1	
4	Home to work	4	Home to doctor	4	Work to home	4	Doctor to home	1		1		1		1		1		1	
4	Home to	4	Home to mall	4	Home to groce	4	Home to	1	Na	1	Na	1	Na	1	Na	1	Na	1	Na

	laundry mat				ry store		visit family												
5	home to work - Jeff	5	home to work - Jackie	3	In laws house	2	Library	2	Bank	1	Grandma's house	2	Woodman's	2	Far m & Fleet	4	YMC A	3	gas station
5	Home to work	4	Home to grocery store	4	Home to zoo	3	Home to Walmart	2	Home to family members homes	2	Home to friends house	4	Home to local restaurants	2	Home to bank	2	Home to park	2	Home to the dells
4	gym	4	grocery store	3	mall	5	work	5	daycare	1		1		1		1		1	
2	grocery store	2	mall	1	Michigan (Parent's home)	2	Exploring	1	work	1	other	1	other	1	other	1	other	1	other
5	Work	5	Daycare	4	Grocery Store	4	Target	4	Gym	2	Gas Station	1	Shopping	1	Hair Salon	1	N/A	1	N/A
2	home to shop	2	home to visit	1	home to restaurant	1	no	1	no	1	no	1	no	1	no	1	no	1	no

			famil y																
5	Home to work	1	Go for an outin g.	4	Dine out.	1		1		1		1		1		1		1	
4	home to work.	2	Go out ot meet frien ds.	4	Eat out.	1	Trav el	1	NA	1	NA	1	NA	1	NA	1	NA	1	NA
5	Home to work	4	Meet frien ds.	5	Ferry my child to and from schoo l.	2	Go out for fun.	1		1		1		1		1		1	
5	Home to work	1	Out for trave l	1		1		1		1		1		1		1		1	
4	Home to work.	5	Deli ver good s.	5	Meet custo mers.	2	Mee t frien ds.	1		1		1		1		1		1	
5	Home to work	2	Go out with my	1		1		1		1		1		1		1		1	

			famil y.																
5	Home to work.	1	Go out with frien ds.	2	Go out with famil y.	1		1		1		1		1		1			
5	home to work	4	hom e to mom 's	2	home to son's	1	hom e to daug hter' s	2	hom e to sister 's	4	home to rich	4	home to grocery	4	hom e to store s	2	home to work out	2	home to restaurant
5	Home to work.	5	Hom e deliv ery servi ce.	5	Meeti ng with client s.	1		1		1		1		1		1		1	
5	Home to work	4	Go out for enter tain ment	2	Go for an outin g.	1		1		1		1		1		1		1	
5	Home to work	4	Hom e to groc ery store	4	Betw een stores shopp ing	2	Ho me to frien ds	3	Hom e to dinn er	2	Hom e to movi e	2	Home to events	2	Hom e to hiki ng	1	Hom e to airpo rt	4	Home to shopping

5	Home to work	2	Go out to tour around with family.	2	Go out for dinner with friends.	1	1	1	1	1	1	1
5	Home to work	4	Home to college	4	Go out	1	1	1	1	1	1	1
5	Work to home.	1		1		1	1	1	1	1	1	1
5	Home to work	2	Go out for dinner with friend	1		1	1	1	1	1	1	1
5	Home to work.	1		1		1	1	1	1	1	1	1
4	Home to work	5	Get child to school	1		1	1	1	1	1	1	1

5	Home to work	2	Go to club	1		1		1		1		1		1		1		1	
4	Home to work	1	Home to my parents	1	Home to her parents	4	Home to grocery store	2	Home to movie theater	4	Home to home improvements store	3	Home to friends' house	4	Work to restaurant	1	Work to satellite office	2	Work to office supply store
5	Home to work	3	Home to parents home	4	home to gym	3	home to store	3	home to friends house	4	home to girlfriends house	4	home to going out to eat	3	rand om drive	2	home to bank	3	madison to milwaukee
5	Home to work	2	Go on an excursion	1		1		1		1		1		1		1		1	
4	Home to work.	5	Visit customers	1		1		1		1		1		1		1		1	
5	Home to work	1		1		1		1		1		1		1		1		1	
4	Home to grocery	4	Home to bar	1	Home to Minnesota	1	Home to	1	Home to West	2	Home to Deerfield	1	Home to Mt Horeb	1	Home to fish	1	Home to up north	1	Home to doctor

South

5	home to school	5	home to store	3	home to other home	2	home to cabin	4	home to VA hospital	1	home to family	4	home to library	2	home to capital	1	home to vacation	1	home to movies
2	Home to work	2	home to store	1	to tennessee	1	none	1	none	1	none	1	none	1	none	1	none	1	none
5	Home to Work	4	Home to Gym	2	Home to State Park	1	Home to Parents	2	Work to Jobsite	2	Home to Grocery Store	2	Home to Restaurant	2	Work to Restaurant	2	Home to Laundromat	4	Home to Frisbee Golf
5	home to school	4	home to friends house	2	home to store	1	home to work	1	home to zoo	3	friends to friends	4	friends to gym	1	home to vacation	2	home to park	3	friends to gym
2	Work	3	Church	4	Shopping	2	Movies	4	Gym	3	Downtown	4	Park	4	Library	4	Groceries	4	Friends home
4	Home to work	5	Meet with clients	1		1		1		1		1		1		1		1	
5	Home to work	5	Home to school	4	Go out eating	1		1		1		1		1		1		1	

4	Home to daycare	2	Daycare to work	2	Home to grocery store	2	Home to shopping locations	1	Home to parent's home	1	Home to St. Paul	1	none	1	none	1	none	1	none
4	Home to work	4	Home to gym	5	Home to drug store	1	Home to seeing family	5	Home to seeing friends	2	Home to shows	5	Home to eat out	3	Home to grocery store	3	Home to pet store	3	Home to meetings
5	Home to work	2	Work-office to out of town	3	Home to store	3	Home to gas station	3	Work to meeting	2	Home to community function	1	Work to airport	1	Home to vacation	1	Home to medical facility	1	Home to restaurant
4	Home to work	4	Home to grocery stores	2	Home to School for sports	2	Home to other schools for sports	2	Home to church	2	Home to YMCA	2	Home to playground for sports	1	Home to Costco	2	Home to relatives house	2	Home to hobby store

5	Home to work	4	Go out	1		1	1	1	1	1	1	1	1	1	1	1			
4	Home to work	2	Go off on a trip	4	Go out for dinner	1	1	1	1	1	1	1	1	1	1	1			
5	Home to work	5	Meet clients	1		1	1	1	1	1	1	1	1	1	1	1			
4	Home to work	2	Meet friends	5	Home to school	1	1	1	1	1	1	1	1	1	1	1			
4	Home to dr office	4	home to daughters house	2	Home to grocery store	2	Home to scrabble club	2	Home to moms house	2	Home to therapist	2	Home to west town	4	Home to walgreens	2	Home to bakery junction	2	Home to target
5	home to work	5	home to gym	4	home to shopping	3	visit family	1	confereces	2	home to library	1	home to restaurant	1	home to milwaukee	1	home to odanah	1	home to ashland
5	Home to work	4	Home to restaurant	1		1	1	1	1	1	1	1	1	1	1	1			

5	Home to work	3	Home to Grocery store	2	Home to Target	2	Home to doctor/c hiro office	3	Work to restaurant	2	Work to friend's house	2	Home to library	2	Home to Walgreens	3	Home to park	1	Home to relative's house
5	Home to school	4	Home to work	4	Home to friend's	1		1		1		1		1		1		1	
4	Mother's	3	Library	3	Father's	2	Grocery store	4	County job center	4	Work	2	Other store(s)	3	Friends'	3	Doctor office	4	Roommate to class
5	Home to work	3	Home to woodmans	2	Gone to target	2	Home to friends homes	1	Gone to recycle center	2	Home to Costco	2	Home to Aldi	2	Home to stoughton conservation club	2	Home to craigslist pickup location	3	Home to church
5	Home to work	5	Home to school	1		1		1		1		1		1		1		1	
5	home to work	4	home to	5	home to	2	home to park	4	home to food	4	home to	2	home to visit family	3	home to gym	1	home to	2	home to gas station

			chur ch		schoo l					frien ds						vacat ion			
5	home to work	2	Go out for an outin g shop ping	4	Eatin g out	1		1		1		1		1		1			
5	home to work	3		1	docto r	1	dent ist	1	dinn er	1	visiti ng	1	library	1	mov ies	1	relati ves	1	voluntee ring
5	Home to work	5	Hom e to scho ol	1		1		1		1		1		1		1			
5	Home to work	2	Meet frien ds.	1		1		1		1		1		1		1			
4		4		4		4		4		4		4		4		4			
4	Home to work	1	Hom e to colle ge apart ment	4	Home to friend s house s	2	Ho me to groc ery store	1	Hom e to auto shop	2	Hom e to city	1	Home to class	3	Hom e to othe r shop s	2	Hom e to mall	3	Home to families house
5	home to school	5	hom e to erran ds	4	home to work	1		1		1		1		1		1			

5	home to work	4	home to stores	4	home to miscellaneous	2	home to doctor appts	2	home to movies	2	home to relatives house	4	home to kids activities	2	home to recreational	2	home to school activities	2	home to just drive around
4	Home to gym	4	Home to grocery	3	Home to library	1	Home to school	1	Home to REI	2	Home to restaurant	1	Home to farmer's market	2	Home to pick up CSA produce	1	Home to son's house	1	Home to bank
5	home to work	2	home church home	4	grocery store home	2	parents home to home	4	Daughters house	2	daughters boyfriend house	2	gas station	2	culvers	1	vet	2	costco
5	Home to work	3	Home to supermarket	2	Home to post office	3	Home to restaurant	2	Work to volunteer sites	2	Home to mall	2	Home to library	1	Home to bank	1	Work to bank	2	Home to family's house
5	Home to work	3	home to campus	1	downtown	2	Gas Station	4	Store	1	movie theater	2	Dinner	1	Doctor	1	Dentist	2	Bar
5	home to stores/	4	home to child's	3	home to work	4	home to child's	3	home to restaurant	1	home to doctor	2	home to hiking/	1	home to airport	1	filling out b/c I	1	filling out b/c I have to

	errands		school		activities		r/dentist		biking/skiing		have to								
2	Home to Grocery	4	Home to Team Practices	3	Home to Shopping	1	Home to Relatives	1	Home to away sports games	1	Home to school	1	Home to work	1	Home to doctors	2	Home to movies	2	Home to Target
2	Home to parents home	3	Home to grocery store	2	Home to work	2	Home to convenience store	2	Home to library	2	Home to friend's house	3	Home to bank	1	Home to restaurant	1	Home to parks	1	Home to gas station
5	Work	4	Boyfriends	3	Shopping mall	4	Bar	4	Friends	2	Out of town	4	Walgreens	3	Store groceries	2	Joyriding	1	Dr
5	home to work	5	home to school	4	home to store	5	home to kids sports	2	home to visit family	4	home to scout s	2	home to kid's friends	3	work to school	2	home to dump	1	home to car repair
2	Home to work	1		1		1		1		1		1		1		1		1	

4	Home to Work	4	Home to School	1	na	1	na	1	na	1	na	1	na	1	na	1	na	1	na
4	Home to work	2	School to home	2	Home to school	2	Home to grocery store	2	Home to friends house	1	School to work	1	School to store	1	Home to mall	1	Home to church	1	School to friends house
2	School	4	Work	3	Sisters	3	Store	1	Library	2	Doctor	2	Grandmas	2	Dinner	2	Dads	3	Friends
5	Home to work	3	Home to grocery	4	Home to work out	5	Home to dog park	2	Home to restaurants	3	Home to school	2	Work to clinic	3	Home to target	1	Home to menards	1	Home to parents
1		2		2		2		1		2		2		2		1		1	
5	Home to work	1	West Chicago	2	shopping	1	none	1	none	1	none	1	none	1	none	1	none	1	none
5	Work	4	Shopping	4	Kids activities	4	Family activities	1		1		1		1		1		1	
5	Home to work	4	Home to Portage	4	Home to Reedsburg	4	Home to Montello	1	Home to Milwaukee	4	Shopping	1	Road trip	2	Church	2	Home to Pardeville	2	Amish area
5	Work to home	4	Doctors to	2	Madison to home	1	Up north to	5	In town and	5	Home to work	4	Home to doctor	1	Home to up	2	Home to	5	Home to in town

			hom e		hom e	hom e			nort h	madi son	
5	home to work	3	shop ping	1	2	2	1	3	3	2	2
4	home to work	1	hom e to hospi tal	1	1	1	1	1	1	1	1
5	Home to work	1		1	1	1	1	1	1	1	1
5	Home to work.	1		1	1	1	1	1	1	1	1
4	Home to work	1		1	1	1	1	1	1	1	1
4	Home to work.	2	frien ds'	1	1	1	1	1	1	1	1
5	Home to work	1		1	1	1	1	1	1	1	1
4	Home to work.	1		1	1	1	1	1	1	1	1
5	home to work	1		1	1	1	1	1	1	1	1

5	Home to work	1	1	1	1	1	1	1	1	1	1
5	Home to work.	1	1	1	1	1	1	1	1	1	1
5	Home to work	1	1	1	1	1	1	1	1	1	1
4	Home to work.	1	1	1	1	1	1	1	1	1	1
5	Home to work	1	1	1	1	1	1	1	1	1	1
4	Home to work.	1	1	1	1	1	1	1	1	1	1
5	Home to work	1	1	1	1	1	1	1	1	1	1
5	Home to work	1	1	1	1	1	1	1	1	1	1
5	Home to work	1	1	1	1	1	1	1	1	1	1
4	home to work	1	1	1	1	1	1	1	1	1	1
5	Home to work	1	1	1	1	1	1	1	1	1	1

5	Home to work	1		1		1		1		1		1		1		1		1		1		1
4	Home to work.	1		1		1		1		1		1		1		1		1		1		1
5	work	1		1		1		1		1		1		1		1		1		1		1
5	Home to work	1		1		1		1		1		1		1		1		1		1		1
4	Home to work	2	A business travel	1		1		1		1		1		1		1		1		1		1
4	Home to work.	1		1		1		1		1		1		1		1		1		1		1
5	Home to work	1		1		1		1		1		1		1		1		1		1		1
4	Home to work.	1		1		1		1		1		1		1		1		1		1		1
5	Home to work	1		1		1		1		1		1		1		1		1		1		1
5	Home to work	1		1		1		1		1		1		1		1		1		1		1
3	home to work	1		1		1		1		1		1		1		1		1		1		1

5	Home to work	1		1		1		1		1		1		1		1		1		1		1
5	Home to work.	1		1		1		1		1		1		1		1		1		1		1
3	Outing	1		1		1		1		1		1		1		1		1		1		1
5	Home to work.	1		1		1		1		1		1		1		1		1		1		1
5	Home to work	1		1		1		1		1		1		1		1		1		1		1
4	Home to work.	1		1		1		1		1		1		1		1		1		1		1
5	Home to work	1		1		1		1		1		1		1		1		1		1		1
5	Home to work	1		1		1		1		1		1		1		1		1		1		1
5	Home to work	1		1		1		1		1		1		1		1		1		1		1
5	Home to work	1		1		1		1		1		1		1		1		1		1		1
5	Home to work	1		1		1		1		1		1		1		1		1		1		1
3	Home to Target	1	Home to gas	1		1		1		1		1		1		1		1		1		1

		station																				
5		1		1		1		1		1		1		1		1		1		1		1
5	Home to work	1		1		1		1		1		1		1		1		1		1		1
5	Home to work	1		1		1		1		1		1		1		1		1		1		1
5	Home to work	1		1		1		1		1		1		1		1		1		1		1
5	Home to work	1		1		1		1		1		1		1		1		1		1		1
5	Home to work	1		1		1		1		1		1		1		1		1		1		1
4	home to work	1		1		1		1		1		1		1		1		1		1		1
3	home to work	1		1		1		1		1		1		1		1		1		1		1
5	Home to work	1		1		1		1		1		1		1		1		1		1		1
4	Home to work	1		1		1		1		1		1		1		1		1		1		1
5	Home to work	3	travel	4	Shop	1		1		1		1		1		1		1		1		1

3	Home to work.	1		1		1		1		1		1		1		1		1	
3	Travel	4	Home to work	4	Out to eat	4	Children to go to school	4	Go to Shop	1	Nothing	1	Nothing	1	Nothing	1	Nothing	1	Nothing
4	work to home	3	Eating out	2	Outing	1		1		1		1		1		1		1	
5	Home to work.	1		1		1		1		1		1		1		1		1	
5	Home to work.	1		1		1		1		1		1		1		1		1	
5	transport goods	3	shopping	1		1		1		1		1		1		1		1	
5	Home to work	1		1		1		1		1		1		1		1		1	
5	Home to work	1		1		1		1		1		1		1		1		1	
4	Home to work	1		1		1		1		1		1		1		1		1	

5	work to home	4	Shop ing	1		1	1	1	1	1	1	1
5	work to home	4	go shop	2	Trave ling	1	1	1	1	1	1	1
4	work to home	3	shop ping	1		1	1	1	1	1	1	1
5	Home to work.	2	frien ds'	1		1	1	1	1	1	1	1
5	Home to work.	1		1		1	1	1	1	1	1	1
5	Home to work	5	Hom e to store	5	Home to schoo l	1	1	1	1	1	1	1
5	Home to work.	1		1		1	1	1	1	1	1	1
3	home to work	1		1		1	1	1	1	1	1	1
3	Home to work.	1		1		1	1	1	1	1	1	1
5	Home to work	1		1		1	1	1	1	1	1	1

5	Home to work	1	1	1	1	1	1	1	1	1
4	Home to work.	1	1	1	1	1	1	1	1	1
4	home to work	1	1	1	1	1	1	1	1	1
4	Home to work.	1	1	1	1	1	1	1	1	1
2	Go to the super marke t	1	1	1	1	1	1	1	1	1

Q7. How often do you use an alternative mode of transportation?

**Table S16** Aggregate survey responses for Q7

Frequency of alternate modes of transportation use	% of respondents
Never	18%
1 to 4 times per month	29%
1 time per week	21%
1 to 4 times per week	21%
5+ times per week	11%

**Table S17** Statistical data for Q7

#	Answer	Bar	Response	%
1	Never	0.181818	36	18%
2	1 to 4 times per month	0.287879	57	29%
3	1 time per week	0.212121	42	21%
4	1 to 4 times per week	0.212121	42	21%
5	5+ times per week	0.106061	21	11%
	Total		198	100%

**Table S18** Statistical data for Q7

Statistic	Value
Min Value	1
Max Value	5
Mean	2.77
Variance	1.61
Standard Deviation	1.27
Total Responses	198

Q8. What type alternative transportation do you use? (Please check all that apply.)

**Table S19** Aggregate survey responses for Q8

Type of alternate transportation used	% of respondents
None	18%
Walk	46%
Bicycle	40%
Bus	41%
Carpool	15%
Other:	8%

**Table S20** Statistical data for Q8

#	Answer	Bar	Response	%
1	None	0.181818	36	18%
2	Walk	0.464646	92	46%
3	Bicycle	0.39899	79	40%
4	Bus	0.414141	82	41%
5	Carpool	0.146465	29	15%
6	Other:	0.075758	15	8%

**Table S21** Statistical data for Q8

Statistic	Value
Min Value	1
Max Value	6
Total Responses	198

Q9. What type(s) of vehicle(s) do you currently own in your household? (Please select "No vehicle" for vehicle numbers beyond that which you own. For example, if your household has three vehicles, please select "No vehicle" for vehicles four-six.)

**Table S22** Aggregate survey responses for Q9

#	Question	No vehicle	Large pickup truck	Small pickup truck	SUV	Hybrid SUV	Large sedan	Small sedan	Hybrid sedan	Coupe (two door)	Other	Total Responses	Mean
1	1 Vehicle	0	6	16	45	10	29	44	23	14	9	196	6.1
2	2 Vehicle	87	5	2	19	3	22	29	4	7	19	197	4.26
3	3 Vehicle	142	0	1	2	2	3	5	2	2	37	196	3.36
4	4 Vehicle	158	0	0	1	0	0	0	0	0	36	195	2.86
5	5 Vehicle	160	0	0	0	0	0	0	0	0	35	195	2.79
6	6 Vehicle	159	0	0	0	0	0	0	0	0	35	194	2.8

**Table S23** Statistical data for Q9

Statistic	Vehicle 1	Vehicle 2	Vehicle 3	Vehicle 4	Vehicle 5	Vehicle 6
Min Value	2	1	1	1	1	1
Max Value	11	11	11	11	11	11
Mean	6.1	4.26	3.36	2.86	2.79	2.8
Variance	5.2	12.2	16.28	15.12	14.8	14.86
Standard Deviation	2.28	3.49	4.04	3.89	3.85	3.86
Total Responses	196	197	196	195	195	194

Q10. What is the model year of each vehicle in your household? (Please select "No vehicle" for vehicle numbers beyond that which you own. For example, if your household has three vehicles, please select "No vehicle" for vehicles four-six.)

**Table S24** Aggregate survey responses for Q10

#	Question	No vehicle	Earlier than 1980	1980-1989	1990-1999	2000-2004	2005-2009	2010-2014	2015-2016	Total Responses	Mean
1	Vehicle 1	0	3	5	19	32	54	65	20	198	6.04
2	Vehicle2	96	1	2	11	11	20	41	16	198	3.73
3	Vehicle 3	175	1	0	2	6	6	6	2	198	1.56
4	Vehicle 4	196	0	0	1	1	0	0	0	198	1.04
5	Vehicle 5	198	0	0	0	0	0	0	0	198	1
6	Vehicle 6	198	0	0	0	0	0	0	0	198	1

**Table S25** Statistical data for Q10

Statistic	Vehicle 1	Vehicle2	Vehicle 3	Vehicle 4	Vehicle 5	Vehicle 6
Min Value	2	1	1	1	1	1
Max Value	8	8	8	5	1	1
Mean	6.04	3.73	1.56	1.04	1	1
Variance	1.75	7.98	2.62	0.13	0	0
Standard Deviation	1.32	2.82	1.62	0.35	0	0
Total Responses	198	198	198	198	198	198

Q11. How many miles per week are each of the vehicles in your household driven? Please provide your best estimate. (Please select "No vehicle" for vehicle numbers beyond that which you own. For example, if your household has three vehicles, please select "No vehicle" for vehicles four-six.)

**Table S26** Aggregate survey responses for Q11

#	Question	No vehicle	1.0-24	25-49	50-99	100-149	150-199	200-249	250+	Total Responses	Mean
1	Vehicle 1	0	0-24	27	44	49	35	16	16	198	4.92
2	Vehicle 2	98	4	17	23	23	16	11	6	198	2.95
3	Vehicle 3	176	5	6	6	2	1	1	1	198	1.31
4	Vehicle 4	196	1	1	0	0	0	0	0	198	1.02
5	Vehicle 5	198	0	0	0	0	0	0	0	198	1
6	Vehicle 6	198	0	0	0	0	0	0	0	198	1

**Table S27** Statistical data for Q11

Statistic	Vehicle 1	Vehicle 2	Vehicle 3	Vehicle 4	Vehicle 5	Vehicle 6
Min Value	2	1	1	1	1	1
Max Value	8	8	8	3	1	1
Mean	4.92	2.95	1.31	1.02	1	1
Variance	2.5	4.98	1.05	0.03	0	0
Standard Deviation	1.58	2.23	1.02	0.16	0	0
Total Responses	198	198	198	198	198	198

Q12. How many times do you fill up the gasoline tank of each vehicle in your household per month? (Please select "No vehicle" for vehicle numbers beyond that which you own. For example, if your household has three vehicles, please select "No vehicle" for vehicles four-six.)

**Table S28** Aggregate survey responses for Q12

#	Question	No vehicle	1	2	3	4	5	6+	Total Responses	Mean
1	Vehicle 1	1	24	61	36	50	7	19	198	4.05
2	Vehicle 2	102	21	23	20	17	7	8	198	2.4
3	Vehicle 3	178	4	6	6	2	0	2	198	1.27
4	Vehicle 4	196	1	1	0	0	0	0	198	1.02
5	Vehicle 5	198	0	0	0	0	0	0	198	1
6	Vehicle 6	198	0	0	0	0	0	0	198	1

**Table S29** Statistical data for Q12

Statistic	Vehicle 1	Vehicle 2	Vehicle 3	Vehicle 4	Vehicle 5	Vehicle 6
Min Value	1	1	1	1	1	1
Max Value	7	7	7	3	1	1
Mean	4.05	2.4	1.27	1.02	1	1
Variance	2.1	3.24	0.87	0.03	0	0
Standard Deviation	1.45	1.8	0.93	0.16	0	0
Total Responses	198	198	198	198	198	198

Q13. At which gasoline price increase amount would you change your driving habits?

**Table S30** Aggregate survey responses for Q13

Gasoline price increase to cause change in driving habits	% of respondents
\$0.50/gal	5%
\$1.00/gal	9%
\$1.50/gal	22%
\$2.00/gal	20%
\$3.00/gal	13%
\$4.00/gal	10%
No price	21%

**Table S31** Statistical data for Q13

Answer	Bar	Response	%
\$0.50/gal	0.050505	10	5%
\$1.00/gal	0.090909	18	9%
\$1.50/gal	0.217172	43	22%
\$2.00/gal	0.19697	39	20%
\$3.00/gal	0.131313	26	13%
\$4.00/gal	0.10101	20	10%
No price increase would change my driving habits	0.212121	42	21%
Total		198	100%

**Table S32** Statistical data for Q13

Statistic	Value
Min Value	1
Max Value	7
Mean	4.42
Variance	3.32
Standard Deviation	1.82
Total Responses	198

Q14. At the gasoline price increase you selected in question 13, how would you change your driving habits? (Please check all that apply.)

**Table S33** Aggregate survey responses for Q14

Change of habit from above fuel price increase	% of respondents
Drive significantly more miles (50% more)	6%
Drive slightly more miles (25% more)	9%
Drive slightly fewer miles (25% fewer)	40%
Drive significantly fewer miles (50% fewer)	18%
Carpool trips more often	21%
Combine trips more often	31%
Use alternative modes of transportation (i.e. bus, bicycle, walk, etc.)	21%
Not change my driving habits	21%

**Table S34** Statistical data for Q14

#	Answer	Bar	Response	%
1	Drive significantly more miles (50% more)	0.0606060	12	6%
2	Drive slightly more miles (25% more)	0.0909090	18	9%
3	Drive slightly fewer miles (25% fewer)	0.3989899	79	40%
4	Drive significantly fewer miles (50% fewer)	0.1818181	36	18%
5	Carpool trips more often	0.2070707	41	21%
6	Combine trips more often	0.3080808	61	31%
7	Use alternative modes of transportation (i.e. bus, bicycle, walk, etc.)	0.2121212	42	21%
8	Not change my driving habits	0.2070707	41	21%

**Table S35** Statistical data for Q14

Statistic	Value
Min Value	1
Max Value	8
Total Responses	198

Q15. Please rank the following vehicle attributes from 1 (most important to you) to 15 (least important to you). Please click and hold on each attribute and drag it to the desired ranking location.

**Table S36** Aggregate survey responses for Q15

Statistic	Fast acceleration	Luxury amenities	Brand loyalty	Efficient fuel economy (35 mpg)	"Greenness"	Influence of others	High performance rating	High power rating
Min Value	1	1	1	1	1	2	1	1
Max Value	15	15	15	15	15	15	14	15
Mean	6.66	6.84	6.46	5.04	7.06	8.81	6.22	8.8
Variance	19.9	20.67	15.69	12.57	12.66	15.62	10.83	9.52
Standard Deviation	4.46	4.55	3.96	3.54	3.56	3.95	3.29	3.09
Total Responses	198	198	198	198	198	198	198	198

Statistic	Price/affordability	High reliability rating	High safety rating	Large size	Sporty style	Cargo space	Passenger seating capacity
Min Value	1	1	1	1	1	2	2
Max Value	15	15	15	15	15	15	15
Mean	6.86	6.88	7.89	10.75	11.21	10.43	10.09
Variance	18.38	15.7	16.52	12.1	14.29	17.47	18.95
Standard Deviation	4.29	3.96	4.06	3.48	3.78	4.18	4.35
Total Responses	198	198	198	198	198	198	198

Q16. In how many years from now do you plan on buying another vehicle?

**Table S37** Aggregate survey responses for Q16

Time until next purchase of vehicle	% of respondents
I have no plans to buy another vehicle	23%
0-1 years	17%
1-3 years	31%
3-5 years	18%
5+ years	11%

**Table S38** Statistical data for Q16

#	Answer	Bar	Response	%
1	I have no plans to buy another vehicle	0.232323	46	23%
2	0-1 years	0.166667	33	17%
3	1-3 years	0.313131	62	31%
4	3-5 years	0.181818	36	18%
5	5+ years	0.106061	21	11%
	Total		198	100%

**Table S39** Statistical data for Q16

Statistic	Value
Min Value	1
Max Value	5
Mean	2.76
Variance	1.65
Standard Deviation	1.29
Total Responses	198

Q17. What type of vehicle do you plan on purchasing?

**Table S40** Aggregate survey responses for Q17

Type of vehicle purchased next	% of respondents
Large pickup truck	3%
Small pickup truck	13%
SUV	32%
Hybrid SUV	13%
Large sedan	12%
Small sedan	16%
Hybrid sedan	8%
Other:	5%

**Table S41** Statistical data for Q17

#	Answer	Bar	Response	%
1	Large pickup truck	0.032895	5	3%
2	Small pickup truck	0.125	19	13%
3	SUV	0.315789	48	32%
4	Hybrid SUV	0.125	19	13%
5	Large sedan	0.118421	18	12%
6	Small sedan	0.157895	24	16%
7	Hybrid sedan	0.078947	12	8%
8	Other:	0.046053	7	5%
	Total		152	100%

**Table S42** Statistical data for Q17

Statistic	Value
Min Value	1
Max Value	8
Mean	4.19
Variance	3.29
Standard Deviation	1.82
Total Responses	152

Other:

don't know

Hatchback

Hatchback

hatchback

performance

minivan

Q18. Will this vehicle be new or used?

**Table S43** Aggregate survey responses for Q18

New or used next vehicle	% of respondents
New	66%
Used	34%

**Table S44** Statistical data for Q18

#	Answer	Bar	Response	%
1	New	0.657895	100	66%
2	Used	0.342105	52	34%
	Total		152	100%

**Table S45** Statistical data for Q18

Statistic	Value
Min Value	1
Max Value	2
Mean	1.34
Variance	0.23
Standard Deviation	0.48
Total Responses	152

Q19. Will this vehicle replace a current vehicle of yours or be an addition to the number of vehicles in your household?

**Table S46** Aggregate survey responses for Q19

Will purchased vehicle replace a currently owned vehicle?	% of respondents
Yes	74%
No	26%

**Table S47** Statistical data for Q19

#	Answer	Bar	Response	%
1	Replace a current vehicle	0.743421	113	74%
2	Addition to the number of vehicles currently owned	0.256579	39	26%
	Total		152	100%

**Table S48** Statistical data for Q19

Statistic	Value
Min Value	1
Max Value	2
Mean	1.26
Variance	0.19
Standard Deviation	0.44
Total Responses	152

Q20. If this vehicle is more fuel efficient than your current vehicle, would you drive more?

**Table S49** Aggregate survey responses for Q20

Will next vehicle purchased be more fuel efficient than current vehicle?	% of respondents
Yes, slightly more (25% more)	23%
Yes, much more (50% more)	29%
No, about the same	45%
No, fewer miles	3%

**Table S50** Statistical data for Q20

#	Answer	Bar	Response	%
1	Yes, slightly more (25% more)	0.230088	26	23%
2	Yes, much more (50% more)	0.292035	33	29%
3	No, about the same	0.451327	51	45%
4	No, fewer miles	0.026549	3	3%
	Total		113	100%

**Table S51** Statistical data for Q20

Statistic	Value
Min Value	1
Max Value	4
Mean	2.27
Variance	0.72
Standard Deviation	0.85
Total Responses	113

Q21. If you saved money on fuel by purchasing a more fuel efficient vehicle, what would you do with the money you saved on fuel?

**Table S52** Aggregate survey responses for Q21

Use of money saved from adoption of fuel efficient vehicle	% of respondents
Drive more	9%
Travel (via non-automobile transportation, such as flying, train, etc.)	17%
Go out to eat more often	16%
Buy more clothes, books, and other consumer goods	18%
Donate to a charity	5%
Deposit it in a bank account or invest it	32%
Other:	3%

**Table S53** Statistical data for Q21

#	Answer	Bar	Response	%
1	Drive more	0.09210	14	9%
2	Travel (via non-automobile transportation, such as flying, train, etc.)	0.17105	26	17%
3	Go out to eat more often	0.15789	24	16%
4	Buy more clothes, books, and other consumer goods	0.17763	27	18%
5	Donate to a charity	0.05263	8	5%
6	Deposit it in a bank account or invest it	0.31578	48	32%
7	Other:	0.03289	5	3%
	Total		152	100%

**Table S54** Statistical data for Q21

Statistic	Value
Min Value	1
Max Value	7
Mean	4.01
Variance	3.3
Standard Deviation	1.82
Total Responses	152

Other:

pay off debt, buy necessities (sic) that have been put off

save it to pay bills

Absorb into household

Pay off debt

Q22. Would increased future fuel prices have any effect on what vehicle you plan to purchase?

**Table S55** Aggregate survey responses for Q22

Would increased future fuel prices have any effect on what vehicle you plan to purchase?	% of respondents
Yes	58%
No	42%

**Table S56** Statistical data for Q22

#	Answer	Bar	Response	%
1	Yes. (Please explain briefly.)	0.580808	115	58%
2	No. (Please explain briefly.)	0.419192	83	42%
	Total		198	100%

**Table S57** Statistical data for Q22

Statistic	Value
Min Value	1
Max Value	2
Mean	1.42
Variance	0.24
Standard Deviation	0.49
Total Responses	198
QID23	QID23-TEXT
1	would consider hybrid vehicle
1	Maybe a smaller truck
2	
2	Gas does not cost enough to make any impact on my budget.
1	if gas is too high, i would buy small fuel efficient car, not an SUV or truck like I would prefer.
1	Need to be cognizant of money we spend as we have a growing family
1	It would make think about the miles per gallon in they city and on the hwy
1	I'd look for something with better mileage

2	
2	
2	Plan to buy a hybrid either way.
1	higher fuel prices would make me value mpg of future purchase more highly
1	Depends on how high the prices are. I'd like to get a Tesla, but they are too expensive right now. If fuel prices get really high (over \$6/gal) and high-range electric vehicles get cheap, I'd buy one.
2	We already look for the most fuel-efficient vehicle and honestly, I drive very little so it impacts me just a little. I wish we would tax gas and use the revenue to pay for transit and active transportation improvements.
2	I already drive a prius and don't drive often, so I hope my next car will be just a fuel efficient and I won't have to increase my driving habits
1	The higher gas price would increase how important fuel economy and a hybrid choice would be
1	I would love a big tahoe or escalade, but if price for fuel went way up, I DEFINITELY wouldn't buy one.
1	I would definitely purchase a highly fuel efficient vehicle if gas prices rose above \$3/gal again.
1	I would tighten my budget in order to buy a hybrid
2	Fuel costs are a small percentage of my monthly expenses
1	The higher gas prices the more aware of fuel economy I am.
1	If gas prices go through the roof, I'd get a more fuel-efficient car
2	Most vehicles and model years we consider buying vary very little as far as MPG goes.
1	Cost of ownership as a whole is a very important factor to me when purchasing.
2	I own a Honda, and it has decent MPG
1	Would get a more gas efficient vehicle.
1	Would not buy a vehicle with a v8 or anything that does not have good gas mileage
1	Not a truck

2	I do not ever plan on purchasing a large suv or pickup truck regardless of gas prices
2	Purchase would depend on my personal needs. If I need to haul things I'll need a bigger vehicle
1	inclined toward smaller fuel efficient vehicle
1	If prices increase, I would definitely look for a fuel efficient car to keep gass needs lower.
1	I would buy a vehicle that is generally fuel efficient that can at least get 30mpg on the highway.
2	I would buy a fuel efficient car regardless of gas prices
1	We would value fuel efficiency even more so.
2	i dont really go for bigger vehicles anyway
2	I plan on keeping my car until I can't drive anymore
1	Depends on the motor size, miles per gallon
2	All ways look for good mpg
1	fuel efficiancy may move up a couple of spots on importance
2	Fuel prices are too volatile to plan purchase around it. Anything with decent mileage 25+ will always be in play for me
1	fuel price increases would be problematic for my budget
1	Need one vehicle in household with good gas mileage and one that can tow/haul
2	Given the size of our family and what I want in a vehicle, fuel prices does not come into play
1	fixed income family...cost controls
2	NOt sure.
1	I will select efficient fuel economy vehicle.
2	No plan to purchase.
2	It will not affect my choice.
2	No affect.
2	I had never think about the case.
2	N/A

1	I would put more emphasis on fuel economy/mpg.
1	I'd like to purchase a car that is low fuel consumption.
2	No plan.
1	More emphasis on fuel efficiency
2	No idea.
2	It is not a problem for me.
2	No need to consider this problem.
2	Increased fuel prices is not a barrier for me to buy the vehicle that I like.
2	No affect.
2	NO IDEA.
2	N/A
2	I only drive my car during the winter. I bike to work all other times, as such gas prices don't affect me that much.
1	would effect mileage
2	N/A
2	No affect.
2	NA
1	I would seek a higher mpg vehicle.
1	Prices are going up all the time, I would prefer a vehicle with better gas mileage.
2	either way, i'm going to buy a car that is the most fuel efficient
1	If the increase in fuel/month costs more than the difference between purchasing ultra-efficiency, I will purchase the ultra-efficient. Likely, I would put more money into a modern motorcycle or a bicycle with pizza-cutter wheels.
1	I would pick a more fuel efficient or smaller car
1	id buy an electric car
2	I have no idea.
2	It's not a barrier for me.
2	Fuel economy is already a priority.

1	Need as fuel efficient as possible
2	Safety is most important.
2	
2	Not sure.
2	No affect.
2	It is not a problem for me.
1	I'd like to buy a vehicle that efficient fuel economy.
	sure fuel efficiency is important at all times as it affects their environment
1	Price plays a part but the carbon footprint is also important
1	efficiency is always an issue and will continue to be.
2	N/A
	You can't predict fuel prices in the long term. You just have to get the best car
2	for your money at the time.
1	i would need an fuel efficient car
	Slightly. I would still strongly desire to purchase a SUV, however may
1	consider a smaller/2 row seating pick-up truck (or other of the like) which was
	a bit more cost efficient when pertaining to gas milage.
	If prices remain low, I am likely to buy a bigger vehicle with more storage and
1	seating capacity
1	I'd like to buy Hybrid vehicle.
1	I would consider a hybrid.
2	No affect.
1	electric car
2	Not sure.
2	No affect.
1	all
1	I would look for a car with better fuel economy.
2	will only purchase a fuel efficient vehicle
2	can't do anything about it so drive accordingly
2	I don't drive much, so increased fuel prices do not have a big impact on me.
1	I can't afford to go if prices go up.

1	Would buy vehicle with better mpg if fuel was more expensive
2	Most of the vehicles I am looking at already have good gas mileage
1	If fuel prices increase significantly I'd consider a smaller, more fuel-efficient vehicle
2	Drive as much as I need to already. Don't drive if I don't have to. Living in DT Madison allows for little to no car usage, outside of having to get outta DT.
2	I feel I am already conscious of possible increases in fuel prices when making vehicle buying and driving decisions,
1	
1	Buy a hybrid
1	Would look for something more fuel efficient.
2	No
1	I would look to buy a more fuel efficient vehicle
2	With cars needing higher MPG according to federal laws, most cars will have a high MPG rating so it won't influence my choice at all.
1	I would consider other options if fuel prices went up dramatically.
2	They are all getting more fuel efficient
1	I would carpool more
2	Gas prices are unpredictable, I always look for fuel efficient vehicles
2	I don't like large vehicles
1	Make decision based on true mpg
1	May buy smaller vehicle
1	Drive less
2	Cheap prices
1	Impact of fuel use price
1	Consider spending
1	Influence car
2	Money
1	Buy a small displacement car
1	Reduce travel

1	Increase budget
1	Reduce the desire to buy a car
2	Useful
1	Influence car
1	Will buy fuel-efficient cars
1	Increase cost
1	new energy vehicles
2	Not much influence
2	Not much influence
1	Increase cost
1	Buy electric cars
1	Reduce the desire to buy a car
1	Influence car
1	Buy electric cars
2	Not much influence
1	Buy a small displacement car
1	Buy a small displacement car
2	It will not have much impact
1	Reduce the desire to buy a car
1	Do not buy a new car
1	Increase cost
2	Not much influence
1	Buy cheap cars
1	Increase cost
1	Buy a small displacement car
2	few times use car
1	Increase cost
2	Not much influence
2	no
1	Have a great connection

1	Have a great connection
1	Reduce the desire to buy a car
1	Buy a small displacement car
1	I would buy one with higher MPG.
1	Influence car
2	Not much influence
1	Have a great connection
2	Not much influence
1	Reduce the desire to buy a car
1	Buy a small displacement car
1	new energy vehicles
2	There will be no big change.
1	Increase cost
1	natural gas
2	Nothing
1	budget
1	I hope that gasoline can be cheaper.
2	Nothing
1	Electric vehicle
1	Not much influence
2	Nothing
2	Not much influence
1	Buy a small displacement car
2	No influence
2	Nothing
2	Nothing
2	Nothing
1	More use of public transport
1	new energy
1	I would carpool or look for a fuel efficient trade in

1	fuel-efficient
1	No gasoline
1	Hybrid electric vehicle
1	Gas vehicle
1	Battery car
1	electric vehicle
1	carpooling
1	new energy
1	Hybrid sedan

Q23. Please specify your age.

**Table S58** Aggregate survey responses for Q23

Age	% of respondents
Under 20 years old	2%
20-29 years old	19%
30-39 years old	49%
40-49 years old	20%
50-59 years old	6%
60-69 years old	4%
70+ years old	1%

**Table S59** Statistical data for Q23

#	Answer	Bar	Response	%
1	Under 20 years old	0.015152	3	2%
2	20-29 years old	0.186869	37	19%
3	30-39 years old	0.489899	97	49%
4	40-49 years old	0.20202	40	20%
5	50-59 years old	0.060606	12	6%
6	60-69 years old	0.040404	8	4%
7	70+ years old	0.005051	1	1%
	Total		198	100%

**Table S60** Statistical data for Q23

Statistic	Value
Min Value	1
Max Value	7
Mean	3.25
Variance	1.08
Standard Deviation	1.04
Total Responses	198

Q24. Please specify your gender.

**Table S61** Aggregate survey responses for Q24

Gender	% of respondents
Male	49%
Female	51%

**Table S62** Statistical data for Q24

#	Answer	Bar	Response	%
1	Male	0.494949	98	49%
2	Female	0.505051	100	51%
	Total		198	100%

**Table S63** Statistical data for Q24

Statistic	Value
Min Value	1
Max Value	2
Mean	1.51
Variance	0.25
Standard Deviation	0.5
Total Responses	198

Q25. Please specify your ethnicity.

**Table S64** Aggregate survey responses for Q25

Ethnicity	% of respondents
Hispanic	28%
Non-Hispanic	72%

**Table S65** Statistical data for Q25

Statistic	Value
Min Value	1
Max Value	2
Mean	1.72
Variance	0.2
Standard Deviation	0.45
Total Responses	198

**Table S66** Statistical data for Q25

Statistic	Value
Min Value	1
Max Value	2
Mean	1.72
Variance	0.2
Standard Deviation	0.45
Total Responses	198

Q26. Please specify your race.

**Table S67** Aggregate survey responses for Q26

Race	% of respondents
Asian/Pacific Islander	11%
Black or African American	12%
Native American	9%
White	65%
Other	3%

**Table S68** Statistical data for Q26

#	Answer	Bar	Response	%
1	Asian/Pacific Islander	0.106061	21	11%
	Black or African			
2	American	0.121212	24	12%
3	Native American	0.090909	18	9%
4	White	0.651515	129	65%
5	Other	0.030303	6	3%
6	Unknown	0	0	0%
	Total		198	100%

**Table S69** Statistical data for Q26

Statistic	Value
Min Value	1
Max Value	5
Mean	3.38
Variance	1.18
Standard Deviation	1.09
Total Responses	198

Q27. Please specify your marital status.

**Table S70** Aggregate survey responses for Q27

Marital status	% of respondents
Single, never married	29%
Married or domestic partnership	58%
Separated	5%
Divorced	7%
Widowed	1%

**Table S71** Statistical data for Q27

#	Answer	Bar	Response	%
1	Single, never married	0.292929	58	29%
2	Married or domestic partnership	0.580808	115	58%
3	Separated	0.045455	9	5%
4	Divorced	0.070707	14	7%
5	Widowed	0.010101	2	1%
	Total		198	100%

**Table S72** Statistical data for Q27

Statistic	Value
Min Value	1
Max Value	5
Mean	1.92
Variance	0.71
Standard Deviation	0.84
Total Responses	198

Q28. Please specify the highest level of education you have completed.

**Table S73** Aggregate survey responses for Q28

Highest level of education completed	% of respondents
No schooling completed	1%
Up to 8th grade	1%
Some high school	1%
High school diploma or equivalent	7%
Some college	17%
Associate's degree	20%
Bachelor's degree	35%
Master's degree	16%
Professional degree	3%
Doctorate degree	1%

**Table S74** Statistical data for Q28

#	Answer	Bar	Response	%
1	No schooling completed	0.005051	1	1%
2	Up to 8th grade	0.005051	1	1%
3	Some high school	0.005051	1	1%
4	High school diploma or equivalent	0.065657	13	7%
5	Some college	0.171717	34	17%
6	Associate's degree	0.20202	40	20%
7	Bachelor's degree	0.353535	70	35%
8	Master's degree	0.161616	32	16%
9	Professional degree	0.025253	5	3%
10	Doctorate degree	0.005051	1	1%
	Total		198	100%

**Table S75** Statistical data for Q28

Statistic	Value
Min Value	1
Max Value	10
Mean	6.41
Variance	1.84
Standard Deviation	1.36
Total Responses	198

Q29. Please specify your living situation.

**Table S76** Aggregate survey responses for Q29

Living situation	% of respondents
Own a house	48%
Rent a house	16%
Own an apartment or condominium	12%
Rent an apartment or condominium	22%
Other:	2%

**Table S77** Statistical data for Q29

#	Answer	Bar	Response	%
1	Own a house	0.484848	96	48%
2	Rent a house	0.156566	31	16%
3	Own an apartment or condominium	0.121212	24	12%
4	Rent an apartment or condominium	0.217172	43	22%
5	Other:	0.020202	4	2%
	Total		198	100%

**Table S78** Statistical data for Q29

Statistic	Value
Min Value	1
Max Value	5
Mean	2.13
Variance	1.65
Standard Deviation	1.28
Total Responses	198

Other:

Sublet

Living with parents to save money to move to Chicago this summer.

live with boyfriend's family

Live with my parents

Q30. Please specify your annual household income level before taxes.

**Table S79** Aggregate survey responses for Q30

Annual household income	% of respondents
Less than \$25,000	7%
\$25,000 to \$34,999	7%
\$35,000 to \$49,999	13%
\$50,000 to \$74,999	24%
\$75,000 to \$99,999	31%
\$100,000 to \$149,999	13%
\$150,000 to \$199,999	6%
\$200,000 or more	1%

**Table S80** Statistical data for Q30

#	Answer	Bar	Response	%
1	Less than \$25,000	0.070707	14	7%
2	\$25,000 to \$34,999	0.065657	13	7%
3	\$35,000 to \$49,999	0.126263	25	13%
4	\$50,000 to \$74,999	0.237374	47	24%
5	\$75,000 to \$99,999	0.313131	62	31%
6	\$100,000 to \$149,999	0.126263	25	13%
7	\$150,000 to \$199,999	0.055556	11	6%
8	\$200,000 or more	0.005051	1	1%
	Total		198	100%

**Table S81** Statistical data for Q30

Statistic	Value
Min Value	1
Max Value	8
Mean	4.28
Variance	2.36
Standard Deviation	1.53
Total Responses	198

Q31. Thank you for your participation. Please specify whether you would like to receive the \$5 Amazon.com digital gift certificate for participating in the survey? If yes, please enter an email address at which you would like to receive the gift code. By selecting "Yes" and entering an email address, you hereby consent to be contacted by the survey administrator for the purpose of receiving the gift code.

**Table S82** Aggregate survey responses for Q31

#	Answer	Bar	Response	%
1	Yes	1	197	100%
2	No	0	0	0%
	Total		197	100%

**Table S83** Statistical data for Q31

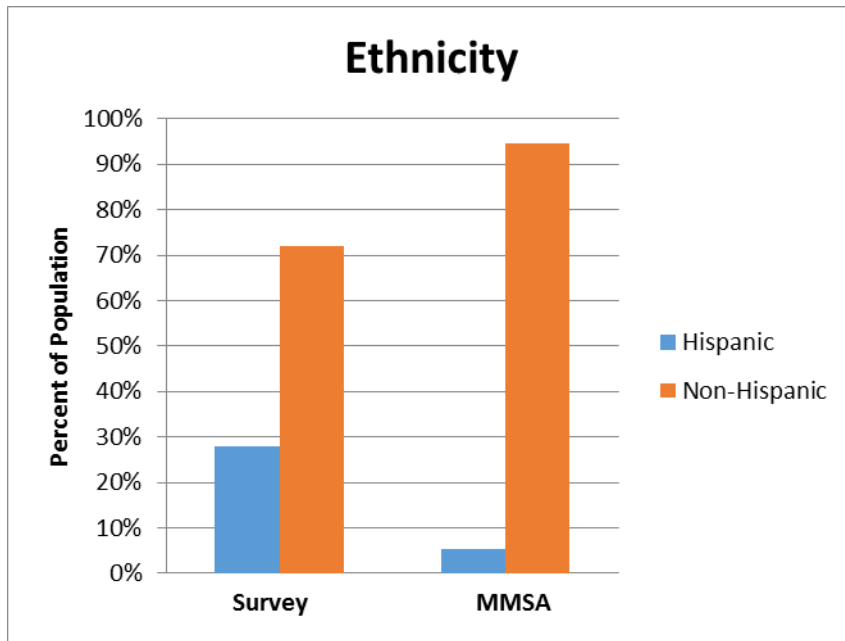
Statistic	Value
Min Value	1
Max Value	1
Mean	1
Variance	0
Standard Deviation	0
Total Responses	197

**Demographic Tables and Figures**

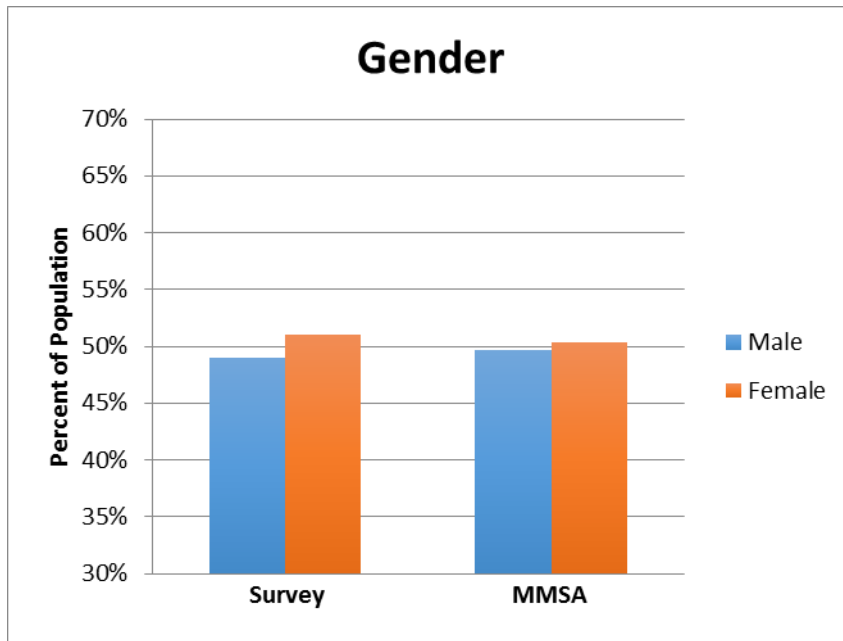
**Table S84** Demographic data for the surveyed population and for the MMSA (United States Census Bureau, 2016)

	Survey Population	MMSA		Survey Population	MMSA
<b>Age</b>	<b>% of respondents</b>		<b>Total population</b>	<b>131</b>	<b>568,593</b>
Under 20 years old	2%	25%	<b>Annual household income</b>	<b>% of respondents</b>	
20-29 years old	19%	17%	Less than \$25,000	7%	18%
30-39 years old	49%	14%	\$25,000 to \$34,999	7%	10%
40-49 years old	20%	14%	\$35,000 to \$49,999	13%	13%
50-59 years old	6%	14%	\$50,000 to \$74,999	24%	20%
60-69 years old	4%	9%	\$75,000 to \$99,999	31%	15%
70+ years old	1%	7%	\$100,000 to \$149,000	13%	14%
<b>Race</b>	<b>% of respondents</b>		\$150,000 to \$199,999	6%	5%
Asian/Pacific Islander	11%	4%	\$200,000 or more	1%	4%

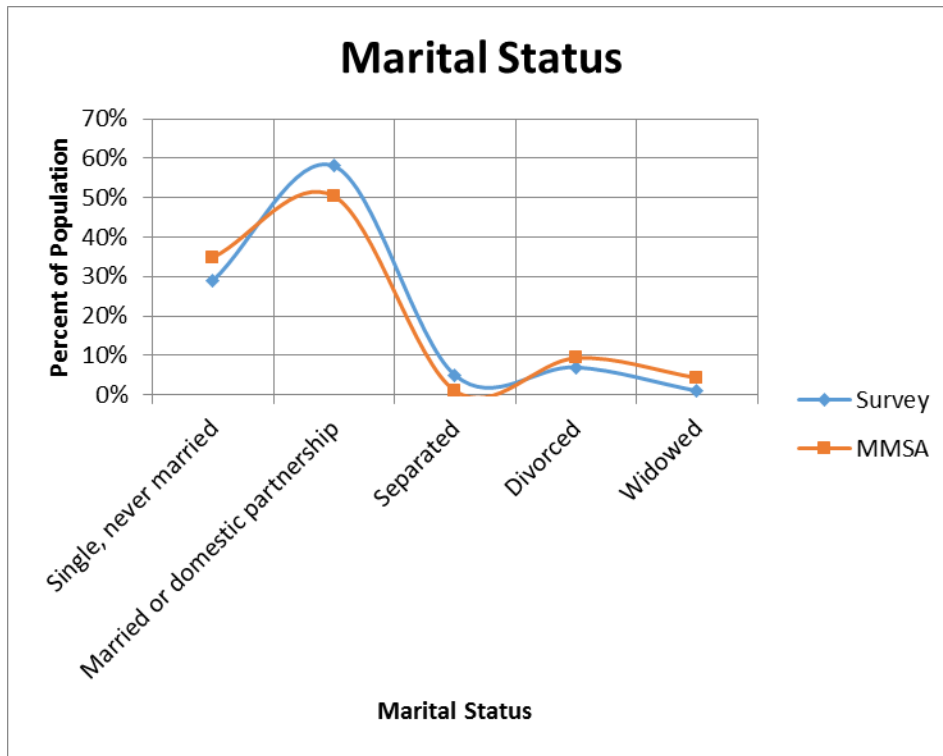
Black/African American	12%	5%	<b>Highest level of education completed</b>	<b>% of respondents</b>	
Native American	9%	0%	Less than 9 <sup>th</sup> grade	2%	2%
White	65%	86%	Some high school	1%	5%
Other	3%	4%	High school diploma or equivalent	7%	24%
<b>Ethnicity</b>	<b>% of respondents</b>		Some college	17%	24%
Hispanic	28%	5%	Associate's degree	20%	9%
Non-Hispanic	72%	95%	Bachelor's degree	35%	24%
<b>Gender</b>	<b>% of respondents</b>		Graduate or professional degree	20%	14%
Male	49%	50%	<b>Marital status</b>	<b>% of respondents</b>	
Female	51%	50%	Single, never married	29%	35%
<b>Living situation</b>	<b>% of respondents</b>		Married or domestic partnership	58%	50%
Own a housing unit	60%	65%	Separated	5%	1%
Rent a housing unit	38%	32%	Divorced	7%	9%
Other	2%	3%	Widowed	1%	4%



**Fig. S1** Ethnicity distribution for the surveyed population and the MMSA



**Fig. S2** Gender distribution for the surveyed population and the MMSA



**Fig. S3** Marital status distribution for the surveyed population and the MMSA

### **3. Additional Survey Methodology**

The survey was split into four general categories, the first of which being generic household data and a cataloging of the vehicle(s) in each household. The vehicle types presented from which to select were large pickup truck (PUT), small PUT, SUV, hybrid SUV, large sedan, small sedan, hybrid sedan, coupe, and other, where “small” was defined as having four cylinder engine and “large” as having greater than four cylinders. The second faction of data honed in on the respondent’s driving tendencies and habits. Thirdly, data was collected to understand the participant’s vehicle purchasing impetus and preferences. This included a ranking importance of vehicle attributes, where the attributes to be ranked were fast acceleration, luxury amenities, brand loyalty, efficient fuel economy, “greenness”, influence of others, high performance rating, high power rating, price/affordability, high reliability rating, high safety rating, large size, sporty style, cargo space, and passenger seating capacity. The final set of information collected was demographics, with categories reflecting those of the U.S. Census Bureau for comparability. A copy of the survey instrument utilized can be found in the appendix.

Qualtrics was the instrument utilized to administer the survey, which was posted publicly on Craigslist. Placement on Craigslist was determined to best reduce sampling bias because responses were not limited to conventional work-day hours nor proximity to the university; any qualified participant within the study area could complete the survey at his or her temporal convenience, only requiring an internet connection. Eligible participants were required to satisfy three criteria: be at least 18 years of age, own at least one vehicle, and be a resident of the Madison Metropolitan Statistical Area (MMSA). The MMSA encompasses Columbia County, Dane County, and Iowa County in Wisconsin (Wisconsin Department of Revenue, 2014). A survey incentive of a \$5 electronic gift certificate was offered to respondents who successfully

completed the survey. Data generated by responses of subjects in breach of one or more of the eligibility criteria were rejected and not used in the analysis. A gross total of 198 eight completed responses were received, with 67 responses rejected on the basis of residence outside the MMSA, netting 131 respondents to be used in this analysis. Surveys not completed were not included in the analysis. The survey instrument and research protocol was approved by the University of Wisconsin-Madison Institutional Review Board (IRB ID 2015-1552). The duration of the study was 66 days from mid-February to late-March 2016.

#### 4. Emission Factors

##### WTP emission factors

**Table S85** Emission factors for total energy in units of MJ total energy/mile

		Vehicle Type							
		Large PUT	Small PUT	SUV	Hybrid SUV	Large Sedan	Small Sedan	Hybrid Sedan	Coupe
Model Year	<1980	2.094E+1	1.569E+1	1.891E+1	NA	1.666E+1	1.379E+1	NA	1.584E+1
	1980-1989	2.094E+1	1.569E+1	1.891E+1	NA	1.666E+1	1.379E+1	NA	1.584E+1
	1990-1999	2.094E+1	1.569E+1	1.891E+1	NA	1.666E+1	1.379E+1	NA	1.584E+1
	2000-2004	2.079E+1	1.591E+1	1.958E+1	NA	1.614E+1	1.396E+1	6.809E+0	1.327E+1
	2005-2009	2.050E+1	1.643E+1	1.837E+1	1.193E+1	1.626E+1	1.335E+1	7.830E+0	1.416E+1
	2010-2014	2.030E+1	1.568E+1	1.576E+1	1.240E+1	1.548E+1	1.188E+1	8.095E+0	1.271E+1
	2015-2016	1.818E+1	1.463E+1	1.493E+1	1.086E+1	1.487E+1	1.170E+1	7.978E+0	1.360E+1

**Table S86** Emission factors for total water use in units of cm<sup>3</sup>/mile

		Vehicle Type							
		Large PUT	Small PUT	SUV	Hybrid SUV	Large Sedan	Small Sedan	Hybrid Sedan	Coupe
Model Year	<1980	1.687E+3	1.264E+3	1.523E+3	NA	1.343E+3	1.111E+3	NA	1.276E+3
	1980-1989	1.687E+3	1.264E+3	1.523E+3	NA	1.343E+3	1.111E+3	NA	1.276E+3
	1990-1999	1.687E+3	1.264E+3	1.523E+3	NA	1.343E+3	1.111E+3	NA	1.276E+3
	2000-2004	1.675E+3	1.282E+3	1.578E+3	NA	1.300E+3	1.125E+3	5.486E+2	1.069E+3
	2005-2009	1.652E+3	1.324E+3	1.480E+3	9.616E+2	1.310E+3	1.076E+3	6.309E+2	1.141E+3
	2010-2014	1.636E+3	1.264E+3	1.270E+3	9.991E+2	1.247E+3	9.571E+2	6.523E+2	1.024E+3
	2015-2016	1.465E+3	1.179E+3	1.203E+3	8.751E+2	1.198E+3	9.427E+2	6.428E+2	1.096E+3

**Table S87** Emission factors for VOC in units of kg VOC/mile

		Vehicle Type							
		Large PUT	Small PUT	SUV	Hybrid SUV	Large Sedan	Small Sedan	Hybrid Sedan	Coupe
Model Year	<1980	2.24E-4	1.68E-4	2.02E-4	NA	1.78E-4	1.47E-4	NA	1.69E-4
	1980-1989	2.24E-4	1.68E-4	2.02E-4	NA	1.78E-4	1.47E-4	NA	1.69E-4
	1990-1999	2.24E-4	1.68E-4	2.02E-4	NA	1.78E-4	1.47E-4	NA	1.69E-4
	2000-2004	2.22E-4	1.70E-4	2.09E-4	NA	1.73E-4	1.49E-4	7.28E-5	1.42E-4
	2005-2009	2.19E-4	1.76E-4	1.96E-4	1.28E-4	1.74E-4	1.43E-4	8.38E-5	1.51E-4
	2010-2014	2.17E-4	1.68E-4	1.69E-4	1.33E-4	1.66E-4	1.27E-4	8.66E-5	1.36E-4
	2015-2016	1.94E-4	1.56E-4	1.60E-4	1.16E-4	1.59E-4	1.25E-4	8.53E-5	1.45E-4

**Table S88** Emission factors for CO in kg CO/mile

		Vehicle Type							
		Large PUT	Small PUT	SUV	Hybrid SUV	Large Sedan	Small Sedan	Hybrid Sedan	Coupe
Model Year	<1980	1.491E-4	1.117E-4	1.346E-4	NA	1.186E-4	9.817E-5	NA	1.128E-4
	1980-1989	1.491E-4	1.117E-4	1.346E-4	NA	1.186E-4	9.817E-5	NA	1.128E-4
	1990-1999	1.491E-4	1.117E-4	1.346E-4	NA	1.186E-4	9.817E-5	NA	1.128E-4
	2000-2004	1.480E-4	1.133E-4	1.394E-4	NA	1.149E-4	9.941E-5	4.848E-5	9.449E-5
	2005-2009	1.459E-4	1.170E-4	1.308E-4	8.497E-5	1.158E-4	9.506E-5	5.575E-5	1.008E-4
	2010-2014	1.445E-4	1.117E-4	1.122E-4	8.828E-5	1.102E-4	8.457E-5	5.764E-5	9.051E-5
	2015-2016	1.295E-4	1.042E-4	1.063E-4	7.732E-5	1.059E-4	8.330E-5	5.680E-5	9.683E-5

**Table S89** Emission factors for NO<sub>x</sub> in kg NO<sub>x</sub>/mile

		Vehicle Type							
		Large PUT	Small PUT	SUV	Hybrid SUV	Large Sedan	Small Sedan	Hybrid Sedan	Coupe
Model Year	<1980	3.155E-4	2.364E-4	2.849E-4	NA	2.511E-4	2.078E-4	NA	2.387E-4
	1980-1989	3.155E-4	2.364E-4	2.849E-4	NA	2.511E-4	2.078E-4	NA	2.387E-4
	1990-1999	3.155E-4	2.364E-4	2.849E-4	NA	2.511E-4	2.078E-4	NA	2.387E-4
	2000-2004	3.133E-4	2.397E-4	2.951E-4	NA	2.432E-4	2.104E-4	1.026E-4	2.000E-4
	2005-2009	3.089E-4	2.476E-4	2.768E-4	1.798E-4	2.450E-4	2.012E-4	1.180E-4	2.133E-4
	2010-2014	3.059E-4	2.364E-4	2.375E-4	1.869E-4	2.333E-4	1.790E-4	1.220E-4	1.916E-4
	2015-2016	2.740E-4	2.205E-4	2.249E-4	1.637E-4	2.241E-4	1.763E-4	1.202E-4	2.049E-4

**Table S90** Emission factors for PM<sub>10</sub> in units of kg PM<sub>10</sub>/mile

		Vehicle Type							
		Large PUT	Small PUT	SUV	Hybrid SUV	Large Sedan	Small Sedan	Hybrid Sedan	Coupe
Model Year	<1980	2.540E-5	1.903E-5	2.294E-5	NA	2.022E-5	1.673E-5	NA	1.921E-5
	1980-1989	2.540E-5	1.903E-5	2.294E-5	NA	2.022E-5	1.673E-5	NA	1.921E-5
	1990-1999	2.540E-5	1.903E-5	2.294E-5	NA	2.022E-5	1.673E-5	NA	1.921E-5
	2000-2004	2.522E-5	1.930E-5	2.376E-5	NA	1.958E-5	1.694E-5	8.261E-6	1.610E-5
	2005-2009	2.487E-5	1.994E-5	2.229E-5	1.448E-5	1.973E-5	1.620E-5	9.500E-6	1.718E-5
	2010-2014	2.463E-5	1.903E-5	1.912E-5	1.504E-5	1.878E-5	1.441E-5	9.821E-6	1.542E-5
	2015-2016	2.206E-5	1.775E-5	1.811E-5	1.318E-5	1.805E-5	1.420E-5	9.680E-6	1.650E-5

**Table S91** Emission factors for PM<sub>2.5</sub> in units of kg PM<sub>2.5</sub>/mile

		Vehicle Type							
		Large PUT	Small PUT	SUV	Hybrid SUV	Large Sedan	Small Sedan	Hybrid Sedan	Coupe
Model Year	<1980	1.671E-5	1.252E-5	1.509E-5	NA	1.330E-5	1.101E-5	NA	1.264E-5
	1980-1989	1.671E-5	1.252E-5	1.509E-5	NA	1.330E-5	1.101E-5	NA	1.264E-5
	1990-1999	1.671E-5	1.252E-5	1.509E-5	NA	1.330E-5	1.101E-5	NA	1.264E-5
	2000-2004	1.659E-5	1.270E-5	1.563E-5	NA	1.288E-5	1.114E-5	5.435E-6	1.059E-5
	2005-2009	1.636E-5	1.312E-5	1.466E-5	9.526E-6	1.298E-5	1.066E-5	6.250E-6	1.130E-5
	2010-2014	1.620E-5	1.252E-5	1.258E-5	9.897E-6	1.236E-5	9.481E-6	6.461E-6	1.015E-5
	2015-2016	1.451E-5	1.168E-5	1.191E-5	8.669E-6	1.187E-5	9.339E-6	6.368E-6	1.086E-5

**Table S92** Emission factors for SO<sub>x</sub> in units of kg SO<sub>x</sub>/mile

		Vehicle Type							
		Large PUT	Small PUT	SUV	Hybrid SUV	Large Sedan	Small Sedan	Hybrid Sedan	Coupe
Model Year	<1980	2.687E-4	2.013E-4	2.426E-04	NA	2.139E-4	1.770E-04	NA	2.033E-4
	1980-1989	2.687E-4	2.013E-4	2.426E-4	NA	2.139E-4	1.770E-4	NA	2.033E-4
	1990-1999	2.687E-4	2.013E-4	2.426E-4	NA	2.139E-4	1.770E-4	NA	2.033E-4
	2000-2004	2.668E-4	2.042E-4	2.513E-4	NA	2.071E-4	1.792E-4	8.739E-05	1.703E-4
	2005-2009	2.631E-4	2.109E-4	2.358E-4	1.532E-4	2.087E-4	1.714E-4	1.005E-4	1.817E-4
	2010-2014	2.606E-4	2.013E-4	2.023E-4	1.591E-4	1.987E-4	1.525E-4	1.039E-4	1.632E-4
	2015-2016	2.334E-4	1.878E-4	1.916E-4	1.394E-4	1.909E-4	1.502E-4	1.024E-4	1.745E-4

**Table S93** Emission factors for CH<sub>4</sub> in units of kg CH<sub>4</sub>/mile

		Vehicle Type							
		Large PUT	Small PUT	SUV	Hybrid SUV	Large Sedan	Small Sedan	Hybrid Sedan	Coupe
Model Year	<1980	6.511E-4	4.878E-4	5.879E-4	NA	5.181E-4	4.288E-4	NA	4.925E-4
	1980-1989	6.511E-4	4.878E-4	5.879E-4	NA	5.181E-4	4.288E-4	NA	4.925E-4
	1990-1999	6.511E-4	4.878E-4	5.879E-4	NA	5.181E-4	4.288E-4	NA	4.925E-4
	2000-2004	6.465E-4	4.947E-4	6.090E-4	NA	5.018E-4	4.342E-4	2.117E-4	4.127E-4
	2005-2009	6.374E-4	5.110E-4	5.712E-4	3.711E-4	5.056E-4	4.152E-4	2.435E-4	4.403E-4
	2010-2014	6.313E-4	4.877E-4	4.902E-4	3.856E-4	4.814E-4	3.694E-4	2.517E-4	3.953E-4
	2015-2016	5.654E-4	4.550E-4	4.642E-4	3.377E-4	4.625E-4	3.639E-4	2.481E-4	4.229E-4

**Table S94** Emission factors for CO<sub>2</sub> in units of kg CO<sub>2</sub>/mile

		Vehicle Type							
		Large PUT	Small PUT	SUV	Hybrid SUV	Large Sedan	Small Sedan	Hybrid Sedan	Coupe
Model Year	<1980	1.451E-1	1.087E-1	1.310E-1	NA	1.154E-1	9.553E-2	NA	1.097E-1
	1980-1989	1.451E-1	1.087E-1	1.310E-1	NA	1.154E-1	9.553E-2	NA	1.097E-1
	1990-1999	1.451E-1	1.087E-1	1.310E-1	NA	1.154E-1	9.553E-2	NA	1.097E-1
	2000-2004	1.440E-1	1.102E-1	1.357E-1	NA	1.118E-1	9.674E-2	4.717E-2	9.194E-2
	2005-2009	1.420E-1	1.138E-1	1.273E-1	8.268E-2	1.126E-1	9.250E-2	5.425E-2	9.809E-2
	2010-2014	1.407E-1	1.087E-1	1.092E-1	8.591E-2	1.073E-1	8.230E-2	5.609E-2	8.808E-2
	2015-2016	1.260E-1	1.014E-1	1.034E-1	7.524E-2	1.031E-1	8.106E-2	5.528E-2	9.422E-2

**Table S95** Emission factors for N<sub>2</sub>O in units of kg N<sub>2</sub>O /mile

		Vehicle Type							
		Large PUT	Small PUT	SUV	Hybrid SUV	Large Sedan	Small Sedan	Hybrid Sedan	Coupe
Model Year	<1980	2.206E-5	1.653E-5	1.992E-5	NA	1.756E-5	1.453E-5	NA	1.669E-5
	1980-1989	2.206E-5	1.653E-5	1.992E-5	NA	1.756E-5	1.453E-5	NA	1.669E-5
	1990-1999	2.206E-5	1.653E-5	1.992E-5	NA	1.756E-5	1.453E-5	NA	1.669E-5
	2000-2004	2.190E-5	1.676E-5	2.063E-5	NA	1.700E-5	1.471E-5	7.174E-6	1.398E-5
	2005-2009	2.160E-5	1.731E-5	1.935E-5	1.257E-5	1.713E-5	1.407E-5	8.250E-6	1.492E-5
	2010-2014	2.139E-5	1.653E-5	1.661E-5	1.306E-5	1.631E-5	1.252E-5	8.529E-6	1.339E-5
	2015-2016	1.916E-5	1.542E-5	1.573E-5	1.144E-5	1.567E-5	1.233E-5	8.406E-6	1.433E-5

**Operation only impact factors**

**Table S96** Emission factors for large pickup truck in unit amount/mile

	Total Energy MJ	Total Water Use n <sup>3</sup>	VOC kg	CO kg	NO <sub>x</sub> kg	PM10 kg	PM2.5 kg	SO <sub>x</sub> kg	CH <sub>4</sub> kg	CO <sub>2</sub> kg	N <sub>2</sub> O kg
2016-2015	5.23E+00	0.00E+00	1.60E-04	7.48E-03	4.60E-04	1.17E-05	1.03E-05	0.00E+00	1.63E-05	3.70E-01	1.14E-05
2010-2014	5.96E+00	0.00E+00	1.80E-04	7.63E-03	5.10E-04	1.18E-05	1.04E-05	0.00E+00	1.70E-05	4.20E-01	4.14E-05
2005-2009	8.01E+00	0.00E+00	5.00E-04	1.88E-02	2.70E-03	1.18E-05	1.04E-05	0.00E+00	8.19E-05	5.50E-01	4.15E-05
2000-2004	8.70E+00	0.00E+00	1.03E-03	1.81E-02	3.38E-03	2.17E-05	1.92E-05	0.00E+00	5.52E-05	6.00E-01	9.26E-05
1990-1999	8.83E+00	0.00E+00	2.05E-03	2.20E-02	2.72E-03	5.16E-05	4.56E-05	0.00E+00	9.28E-05	6.00E-01	5.40E-05
1980-1989	8.83E+00	0.00E+00	2.05E-03	2.20E-02	2.72E-03	5.16E-05	4.56E-05	0.00E+00	9.28E-05	6.00E-01	5.40E-05

**Table S97** Emission factors for small pickup truck in unit amount/mile

	Total Energy MJ	Total Water Use n <sup>3</sup>	VOC kg	CO kg	NO <sub>x</sub> kg	PM10 kg	PM2.5 kg	SO <sub>x</sub> kg	CH <sub>4</sub> kg	CO <sub>2</sub> kg	N <sub>2</sub> O kg
2016-2015	4.12E+00	0.00E+00	1.60E-04	7.48E-03	4.60E-04	1.17E-05	1.03E-05	0.00E+00	1.63E-05	2.90E-01	1.14E-05
2010-2014	4.69E+00	0.00E+00	1.80E-04	7.63E-03	5.10E-04	1.18E-05	1.04E-05	0.00E+00	1.70E-05	3.30E-01	4.14E-05
2005-2009	6.34E+00	0.00E+00	5.00E-04	1.88E-02	2.70E-03	1.18E-05	1.04E-05	0.00E+00	8.19E-05	4.30E-01	4.15E-05
2000-2004	6.86E+00	0.00E+00	1.03E-03	1.81E-02	3.38E-03	2.47E-05	1.92E-05	0.00E+00	5.52E-05	4.70E-01	9.26E-05
1990-1999	6.96E+00	0.00E+00	2.05E-03	2.20E-02	2.72E-03	5.16E-05	4.56E-05	0.00E+00	9.28E-05	4.60E-01	5.54E-05
1980-1989	6.96E+00	0.00E+00	2.05E-03	2.20E-02	2.72E-03	5.16E-05	4.56E-05	0.00E+00	9.28E-05	4.60E-01	5.54E-05

**Table S98** Emission factors for SUV in unit amount/mile

	Total Energy	Total Water Use	VOC	CO	NO <sub>x</sub>	PM10	PM2.5	SO <sub>x</sub>	CH <sub>4</sub>	CO <sub>2</sub>	N <sub>2</sub> O
	MJ	n <sup>3</sup>	kg	kg	kg	kg	kg	kg	kg	kg	kg
2016-2015	4.42E+00	0.00E+00	1.10E-04	3.09E-03	1.60E-04	7.01E-06	6.20E-06	0.00E+00	1.10E-05	3.20E-01	6.31E-06
2010-2014	5.11E+00	0.00E+00	1.30E-04	3.20E-03	1.70E-04	7.10E-06	6.28E-06	0.00E+00	1.19E-05	3.70E-01	9.53E-06
2005-2009	6.84E+00	0.00E+00	2.10E-04	3.80E-03	3.60E-04	7.17E-06	6.35E-06	0.00E+00	2.05E-05	4.90E-01	9.57E-06
2000-2004	7.26E+00	0.00E+00	8.90E-04	7.31E-03	1.51E-03	1.31E-05	1.15E-05	0.00E+00	3.78E-05	5.10E-01	4.27E-05
1990-1999	7.13E+00	0.00E+00	1.54E-03	1.61E-02	2.64E-03	2.94E-05	2.60E-05	0.00E+00	6.48E-05	4.90E-01	7.29E-05
1980-1989	7.13E+00	0.00E+00	1.54E-03	1.61E-02	2.64E-03	2.94E-05	2.60E-05	0.00E+00	6.48E-05	4.90E-01	7.29E-05

**Table S99** Emission factors for hybrid in unit amount/mile

	Total Energy	Total Water Use	VOC	CO	NO <sub>x</sub>	PM10	PM2.5	SO <sub>x</sub>	CH <sub>4</sub>	CO <sub>2</sub>	N <sub>2</sub> O
	MJ	n <sup>3</sup>	kg	kg	kg	kg	kg	kg	kg	kg	kg
2016-2015	3.27E+00	0.00E+00	5.98E-05	3.09E-03	1.30E-04	7.01E-06	6.20E-06	0.00E+00	5.17E-06	2.30E-01	6.31E-06
2010-2014	3.79E+00	0.00E+00	6.76E-05	3.20E-03	1.50E-04	7.10E-06	6.28E-06	0.00E+00	5.60E-06	2.70E-01	9.53E-06
2005-2009	5.07E+00	0.00E+00	1.10E-04	3.80E-03	3.00E-04	7.17E-06	6.35E-06	0.00E+00	9.65E-06	3.60E-01	9.57E-06
2000-2004	7.26E+00	0.00E+00	7.80E-04	7.31E-03	1.51E-03	1.31E-05	1.15E-05	0.00E+00	3.78E-05	5.10E-01	4.27E-05
1990-1999	7.13E+00	0.00E+00	1.54E-03	1.61E-02	2.64E-03	2.94E-05	2.60E-05	0.00E+00	6.58E-05	4.90E-01	7.29E-05
1980-1989	7.13E+00	0.00E+00	1.54E-03	1.61E-02	2.64E-03	2.94E-05	2.60E-05	0.00E+00	6.58E-05	4.90E-01	7.29E-05

**Table S100** Emission factors for large sedan in unit amount/mile

	Total Energy	Total Water Use	VOC	CO	NO <sub>x</sub>	PM10	PM2.5	SO <sub>x</sub>	CH <sub>4</sub>	CO <sub>2</sub>	N <sub>2</sub> O
	MJ	n <sup>3</sup>	kg	kg	kg	kg	kg	kg	kg	kg	kg
2016-2015	4.12E+00	0.00E+00	1.20E-04	2.57E-03	1.10E-04	5.29E-06	4.68E-06	0.00E+00	7.90E-06	2.90E-01	4.89E-06
2010-2014	4.54E+00	0.00E+00	1.30E-04	2.70E-03	1.20E-04	5.41E-06	4.78E-06	0.00E+00	8.64E-06	3.30E-01	7.62E-06
2005-2009	5.06E+00	0.00E+00	2.30E-04	3.13E-03	2.10E-04	5.48E-06	4.85E-06	0.00E+00	1.53E-05	3.60E-01	7.64E-06
2000-2004	5.38E+00	0.00E+00	5.10E-04	4.83E-03	1.03E-03	9.27E-06	8.20E-06	0.00E+00	1.57E-05	3.80E-01	1.90E-05
1990-1999	5.36E+00	0.00E+00	8.30E-04	6.84E-03	1.29E-03	2.36E-05	2.09E-05	0.00E+00	4.89E-05	3.80E-01	3.54E-05
1980-1989	5.36E+00	0.00E+00	8.30E-04	6.84E-03	1.29E-03	2.36E-05	2.09E-05	0.00E+00	4.89E-05	3.80E-01	3.54E-05

**Table S101** Emission factors for small sedan in unit amount/mile

	Total Energy	Total Water Use	VOC	CO	NO <sub>x</sub>	PM10	PM2.5	SO <sub>x</sub>	CH <sub>4</sub>	CO <sub>2</sub>	N <sub>2</sub> O
	MJ	n <sup>3</sup>	kg	kg	kg	kg	kg	kg	kg	kg	kg
2016-2015	3.15E+00	0.00E+00	1.20E-04	2.57E-03	1.10E-04	5.29E-06	4.68E-06	0.00E+00	7.90E-06	2.20E-01	4.89E-06
2010-2014	3.48E+00	0.00E+00	1.30E-04	2.70E-03	1.20E-04	5.41E-06	4.78E-06	0.00E+00	8.64E-06	2.50E-01	7.62E-06
2005-2009	3.87E+00	0.00E+00	2.30E-04	3.13E-03	2.10E-04	5.48E-06	4.85E-06	0.00E+00	1.53E-05	2.80E-01	7.64E-06
2000-2004	4.12E+00	0.00E+00	5.10E-04	4.83E-03	1.03E-03	9.27E-06	8.20E-06	0.00E+00	1.57E-05	2.90E-01	1.90E-05
1990-1999	4.10E+00	0.00E+00	8.30E-04	6.84E-03	1.29E-03	3.26E-05	2.09E-05	0.00E+00	4.89E-05	2.80E-01	3.54E-05
1980-1989	4.10E+00	0.00E+00	8.30E-04	6.84E-03	1.29E-03	3.26E-05	2.09E-05	0.00E+00	4.89E-05	2.80E-01	3.54E-05

**Table S102** Emission factors for hybrid sedan in unit amount/mile

	Total Energy	Total Water Use	VOC	CO	NO <sub>x</sub>	PM10	PM2.5	SO <sub>x</sub>	CH <sub>4</sub>	CO <sub>2</sub>	N <sub>2</sub> O
	MJ	n <sup>3</sup>	kg	kg	kg	kg	kg	kg	kg	kg	kg
2016-2015	2.94E+00	0.00E+00	6.33E-05	2.57E-03	9.28E-05	.000005.29	4.68E-06	0.00E+00	3.71E-06	2.10E-01	4.89E-06
2010-2014	3.24E+00	0.00E+00	7.27E-05	2.70E-03	1.00E-04	5.41E-06	4.78E-06	0.00E+00	4.06E-06	2.30E-01	7.62E-06
2005-2009	3.61E+00	0.00E+00	1.20E-04	3.13E-03	1.70E-04	5.48E-06	4.85E-06	0.00E+00	7.17E-05	2.60E-01	7.64E-06
2000-2004	3.61E+00	0.00E+00	1.20E-04	3.13E-03	1.70E-04	5.48E-06	4.85E-06	0.00E+00	7.17E-05	2.60E-01	7.64E-06
1990-1999	3.61E+00	0.00E+00	1.20E-04	3.13E-03	1.70E-04	5.48E-06	4.85E-06	0.00E+00	7.17E-05	2.60E-01	7.64E-06
1980-1989	3.61E+00	0.00E+00	1.20E-04	3.13E-03	1.70E-04	5.48E-06	4.85E-06	0.00E+00	7.17E-05	2.60E-01	7.64E-06

**Table S103** Emission factors for coupe in unit amount/mile

	Total Energy	Total Water Use	VOC	CO	NO <sub>x</sub>	PM10	PM2.5	SO <sub>x</sub>	CH <sub>4</sub>	CO <sub>2</sub>	N <sub>2</sub> O
	MJ	n <sup>3</sup>	kg	kg	kg	kg	kg	kg	kg	kg	kg
2016-2015	3.15E+00	0.00E+00	1.20E-04	2.57E-03	1.10E-04	5.29E-06	4.68E-06	0.00E+00	7.90E-06	2.20E-01	4.89E-06
2010-2014	3.48E+00	0.00E+00	1.30E-07	2.70E-03	1.20E-04	5.41E-06	4.78E-06	0.00E+00	8.64E-06	2.50E-01	7.62E-06
2005-2009	3.87E+00	0.00E+00	2.30E-04	3.13E-03	2.10E-04	5.48E-06	4.85E-06	0.00E+00	1.53E-05	2.80E-01	7.64E-06
2000-2004	4.12E+00	0.00E+00	5.10E-04	4.83E-03	1.03E-03	9.27E-06	8.20E-06	0.00E+00	1.57E-05	2.90E-01	1.90E-05
1990-1999	4.10E+00	0.00E+00	8.30E-04	6.84E-03	1.29E-03	2.36E-05	2.09E-05	0.00E+00	4.89E-05	2.80E-01	3.54E-05
1980-1989	4.10E+00	0.00E+00	8.30E-04	6.84E-03	1.29E-03	2.36E-05	2.09E-05	0.00E+00	4.89E-05	2.80E-01	3.54E-05

**Table S104** Translation of NHTS vehicle type classification into vehicle types useable for this study.

<b>NHTS Marker</b>	<b>NHTS Vehicle Type</b>	<b>Assigned Study Vehicle Type</b>
-1	Appropriate skip	Large sedan*
-7	Refused	Large sedan*
-8	Don't know	Large sedan*
-9	Not ascertained	Large sedan*
1	Auto/car/station wagon	Small sedan
2	Van	SUV
3	SUV	SUV
4	Pickup truck	Small pickup truck
5	Other truck	Large pickup truck
6	RV/recreational vehicle	Large pickup truck
7	Motor cycle	Small sedan
8	Golf cart	Coupe
97	Other	Large sedan

\* Large sedan was used when no vehicle type was provided in order to generate data to represent that weighted section of the general population. It was determined that the miles per gallon data for a large sedan was an intermediate value when compared with the other vehicle types.

**Table S105** Vehicle mileage ranges used as miles driven data for impact calculations (miles)

<b>Low bound</b>	<b>Mid value</b>	<b>High bound</b>
1	12.5	24
24	37	49
50	74.5	99
100	124.5	149
150	174.5	199
200	224.5	249
250	275	300

**Table S106** Vehicle types used in the study and the corresponding GREET vehicle types

Study Vehicle Type	GREET Vehicle Type
Large PUT	PUT: SI ICEV - E10 (Type 1 Conventional Material)
Small PUT	PUT: SI ICEV - E10 (Type 1 Lightweight Material)
SUV	SUV: SI ICEV - E10 (Type 1 Conventional Material)
Hybrid SUV	SUV: SI HEV - E10 (Type 1 Ni-MH Conventional Material)
Large Sedan	Car: SI ICEV - E10 (Type 1 Conventional Material)
Small Sedan	Car: SI ICEV - E10 (Type 1 Lightweight Material)
Hybrid Sedan	Car: SI HEV - E10 (Type 1 Ni-MH Conventional Material)
Coupe	Car: SI ICEV - E10 (Type 1 Lightweight Material)

**Table S107** Environmental impacts of personal transportation for Wisconsin. Total impact, change in total impact, impact per person, and change in impact per person are presented from NHTS years 2009 and 2001

	Total Energy (MJ)	Total Water (m <sup>3</sup> )	VOC (kg)	CO (kg)	NO <sub>x</sub> (kg)	PM10 (kg)	PM2.5 (kg)	SO <sub>x</sub> (kg)	CH <sub>4</sub> (kg)	CO <sub>2</sub> (kg)	N <sub>2</sub> O (kg)
<b>Total Impact</b>											
2009	1.03E+12	6.48E+7	4.98E+7	3.46E+8	6.96E+7	4.23E+6	1.18E+6	1.01E+7	2.61E+7	2.22E+10	2.27E+6
2001	1.01E+12	6.02E+7	6.15E+7	5.47E+8	9.84E+7	2.37E+6	1.72E+6	9.59E+6	2.59E+7	2.29E+10	2.94E+6
<b>Change in Total Impact</b>											
2009	2.0E+10	4.6E+6	-1.2E+7	-2.0E+8	-2.9E+7	1.9E+6	-5.38E+5	5.4E+5	1.6E+5	-6.8E+8	-6.7E+5
(%)	2%	8%	-19%	-37%	-29%	78%	-31%	5%	1%	-3%	-23%
<b>Impact Per Person</b>											
2009	2.29E+5	1.44E+1	1.10E+1	7.68E+1	1.54E+1	9.39E-1	2.63E-1	2.25E+0	5.79E+0	4.92E+3	5.03E-1
2001	2.36E+5	1.40E+1	1.43E+1	1.27E+2	2.29E+1	5.52E-1	4.01E-1	2.24E+0	6.04E+0	5.33E+3	6.85E-1
<b>Change in Impact Per Person</b>											
2009	-7.01E+3	3.37E-1	3.28E+0	5.06E+1	7.48E+0	3.86E-01	-1.39E-1	1.29E-2	-2.55E-1	-4.06E+2	-1.82E-1
(%)	-3%	3%	-23%	-40%	-33%	70%	-34%	0%	-4%	-8%	-27%

**Table S108** Environmental impacts of personal transportation for the Milwaukee MSA. Total impact, change in total impact, impact per person, and change in impact per person are presented from NHTS years 1990 and 1995

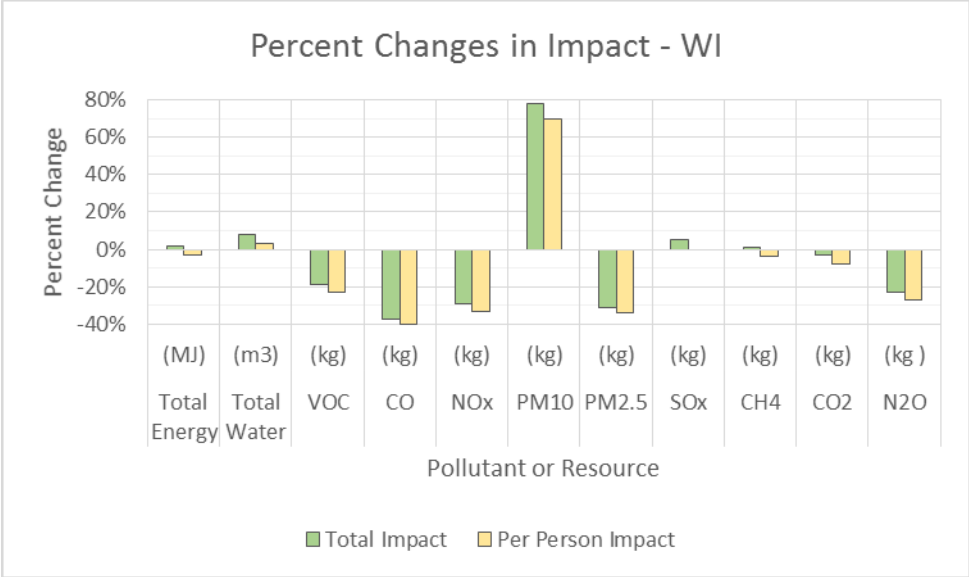
	Total Energy (MJ)	Total Water (m <sup>3</sup> )	VOC (kg)	CO (kg)	NO <sub>x</sub> (kg)	PM10 (kg)	PM2.5 (kg)	SO <sub>x</sub> (kg)	CH <sub>4</sub> (kg)	CO <sub>2</sub> (kg)	N <sub>2</sub> O (kg)
<b>Total Impact</b>											
1995	2.13E+11	1.29E+7	1.29E+7	1.04E+8	2.00E+7	5.53E+5	3.82E+5	2.06E+6	5.58E+6	4.69E+9	6.38E+5
1990	1.85E+11	1.14E+7	1.08E+7	8.17E+7	1.64E+7	5.04E+5	3.36E+5	1.81E+6	4.90E+6	3.97E+9	8.75E+6
<b>Change in Total Impact</b>											
1995	2.80E+10	1.50E+6	2.10E+6	2.23E+7	3.60E+6	4.90E+4	4.60E+4	2.50E+5	6.80E+5	7.20E+8	8.11E+6
(%)	15%	13%	19%	27%	22%	10%	14%	14%	14%	18%	-93%
1990	-	-	-	-	-	-	-	-	-	-	-
<b>Impact Per Person</b>											
1995	2.50E+5	1.52E+1	1.52E+1	1.22E+2	2.35E+1	6.50E-1	4.49E-1	2.42E+0	6.56E+0	5.51E+3	7.49E-1
1990	2.18E+5	1.34E+1	1.27E+1	9.66E+1	1.94E+1	5.96E-1	3.97E-1	2.14E+0	5.79E+0	4.69E+3	6.27E-1
<b>Change in Impact Per Person</b>											
1995	3.20E+4	1.80E+0	2.50E+0	2.54E+1	4.10E+0	5.40E-2	5.20E-2	2.80E-1	7.70E-1	8.20E+2	1.22E-1
(%)	15%	13%	20%	26%	21%	9%	13%	13%	13%	17%	19%
1990	-	-	-	-	-	-	-	-	-	-	-

**Equation S1** Initial level of fuel consumption  $f_{1,i}$  for participant  $i$ , where  $d_i$  is distance driven,  $e_z$  is the efficiency of vehicle  $z$ , and  $w_i$  is the weighting factor

$$f_{1,i} = \frac{d_i}{e_z} \cdot w_i \quad (S1)$$

**Equation S2** Fuel consumption after adoption  $f_{2,i}$ , where  $\alpha$  is the anticipated percent increase in miles driven following adoption (no increase, 25% increase, or 50% increase)

$$f_{2,i} = f_{1,i} \cdot (1 + \alpha) \quad (S2)$$

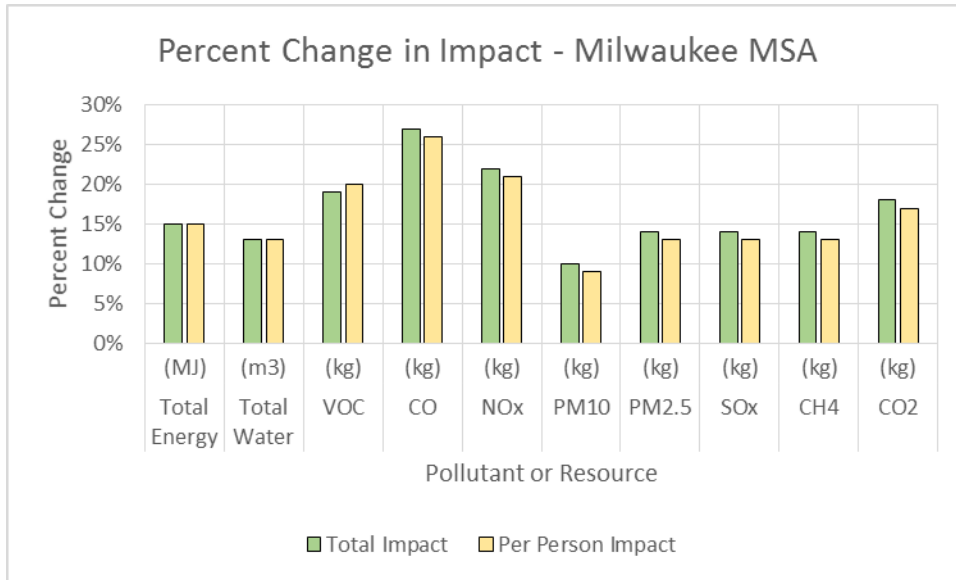


**Figure S4.** Percent change between 2001 and 2009 in state of Wisconsin.

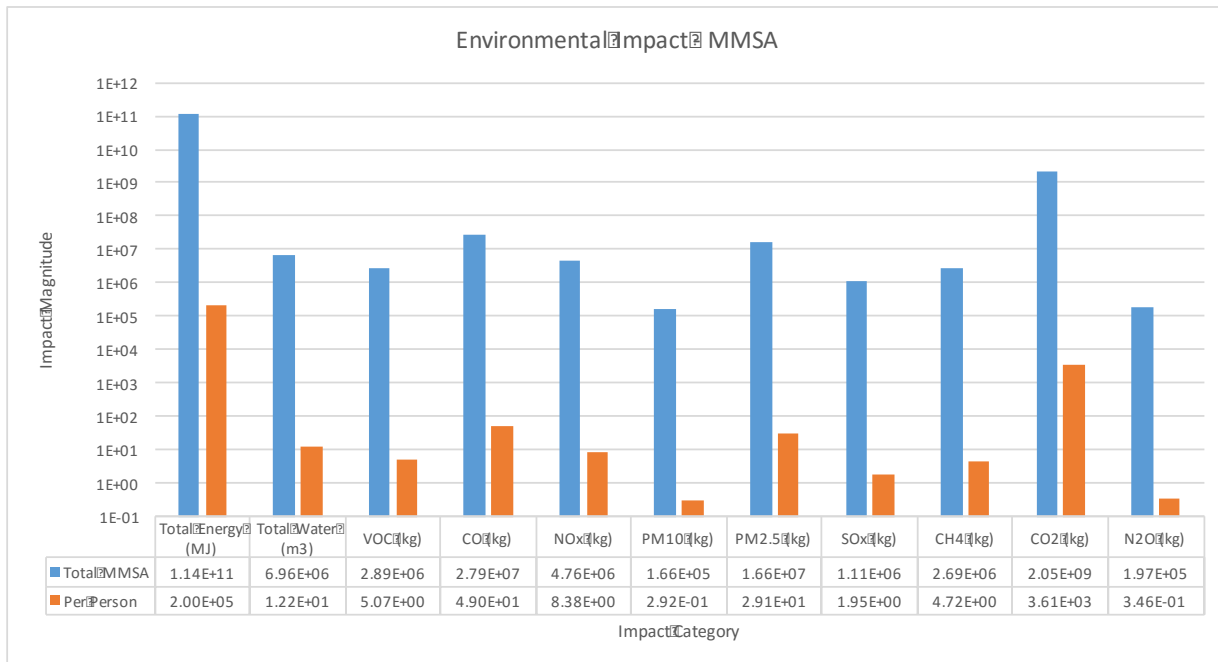
An interesting observation from Figure 8 is the marked increase in PM10. A potential source of this sizeable increase may be associated with the increase in miles driven and its implications within the fuel cycle through a rise in both combustion of diesel and coal along with particulate matter kicked up into the atmosphere (EPA, 2016). Both prospective sources would solely be associated with the fuel cycle, as the operation only phase in this study solely encompassed E10 gasoline and its combustion, not diesel combustion or tire and break wear. The increase in miles driven and consequent increase in fuel consumed (section 3.3.3 and Figure 16) would require an uptick in fuel production, which may likely lead to an increase in impacts associated with the fuel cycle. The large equipment used to extract and transport crude oil has a high propensity to kick up dust and other PM10, while simultaneously emitting PM2.5 via combustion of diesel as a fuel. Furthermore, the refineries are large consumers of coal-generated electricity and flare off gas, both of which emit PM (RTI International, 2011). With the increase in vehicle fuel consumed at the consumer level, these impacts increase throughout the fuel cycle, which may

explain the observed increase in PM10. It is relevant to understand that the main source of PM2.5 is combustion of fuels (notably coal and diesel, among others) and that PM10 (which encompasses PM2.5) commonly comes from non-combustion sources, such as atmospheric dust and wear of tires and brakes (Querol et al, 2001). Thus, improvements in efficiency may lead to reduced PM2.5, while a corresponding increase in miles driven and fuel demand may cause an increase in PM10.

Within the impact calculation methodology, the 70% increase in PM10 can be attributed to the PM10 WTP emission factors exhibiting an appreciably larger increase than other impact categories for small sedans and SUVs older than model year 1999, where 82% of vehicles in the 2009 dataset were small sedans or SUVs and 75% of vehicles were older than model year 1999; the 2001 dataset had 81% of the vehicles as small sedans or SUVs and 86% of vehicles were older than model year 1999. With these two vehicle types of the given model year comprising a strong majority of vehicles in the dataset, their respective emission factors drove the impact trends. Compared to the other ten impact categories, the emission factors for PM10 for these particular vehicles increased by a significantly larger margin, causing the large percent increase in PM10 and not in the other impact categories.



**Figure S5.** Percent change in impact between 1990 and 1995 in Milwaukee MSA.



**Figure S6.** Total impact for MMSA and per person.