Fuel Usage of Selected Road Vehicles Operating on Common and Alternative Fuels in Iceland 2009-2010

Incorporating Driving Behavior and Vehicle Characteristics

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Abstract

This study examines variables that affect fuel consumption of road vehicles, such as driving behavior, vehicle characteristics, and the difference between fuels used. The objectives were to gather data from a selection of road vehicles that were fuelled with alternative fuels (gasoline, diesel, methane, hydrogen) in Iceland and to identify the difference in vehicle efficiency as a measure of the vehicles' fuel consumption. The goal is to provide recommendations to decrease the overall emission from the transport sector in Iceland. Data was collected with SAGAsystem™ GPS monitoring devices and fuel cards. A linear regression was performed on the amount of gasoline for each refill as a function of observed variables. The results show that acceleration has a statistically significant effect on the vehicles' fuel consumption. In order to minimize fuel consumption, speed must be increased with a moderate acceleration and average speed should be as steady as possible. Hydrogen and Methane provided the overall best results in fuel consumption when compared with the other types of fuels, and with all other factors kept fixed. The Toyota Prius hybrid vehicles use regenerative braking and the frequency of severe braking instances causes a statistically significant less energy consumption for these vehicles. It is recommended that for future research on energy consumption of vehicles, that a fuel monitor computer be installed in each vehicle in order to gain better data for analysis within each refill period. These results should be taken into consideration when developing policy or plans to decrease the total emissions from the road transport sector in Iceland.

Útdráttur

Í þessari rannsókn voru skoðuð áhrif ýmissa þátta á orkunotkun bifreiða, svo sem aksturslag, tæknilegir eiginleikar bifreiða og mismunandi eldsneyti. Markmið rannsóknarinnar var að safna gögnum frá mismunandi bifreiðum sem notuðu mismunandi eldsneyti (bensín, dísil, metan, vetni) á Íslandi og að fá upplýsingar um mismun í nýtni þeirra miðað við orkunotkun bifreiðanna. Tilgangurinn er að koma með tillögur til að draga úr útblæstri frá bifreiðum á Íslandi. Gögn fengust úr SAGAsystem™ ökuritum og frá eldsneytiskortum. Gerð var aðhvarfsgreining á magni eldsneytis við hverja áfyllingu sem fall af mældum stærðum. Niðurstöður sýna að hröðun hefur tölfræðilega marktæk áhrif á orkunotkun bifreiðar. Draga má úr orkunotkun með því að auka hraða rólega og halda almennt sem jöfnustum hraða. Vetni og metan komu best út í eldsneytissamanburði þegar öllum öðrum þáttum var haldið stöðugum. Toyota Prius tvinnbifreiðarnar endurheimta orku við hemlun og aukin hemlun veldur marktækt minni orkunotkun hjá þessum ökutækjum. Mælt er með að í framtíðinni verði eldsneytisnotkun mæld stöðugt með akstursstölvu í hverri bifreið til að fá betri greiningar innan áfyllingartímabils. Taka ætti tillit til þessara niðurstaða þegar unnið er að þróun reglugerða og skipulags fyrir samdrátt í losun á gróðurhúsaloftegundum frá vegasamgöngum á Íslandi.

Dedication

Einar Máni, Sólveig Þórhallsdóttir, Lárus Einarsson

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1 Introduction

In the year 2004, the total emission of greenhouse gases (GHG) from the passenger vehicle sector was around 23% of the world's total GHG output from energy consumption (6.3 Gt CO_2) (WBCSD, 2001). This number has increased by about 27% since the year 1990 (IEA, 2006). There are mainly two ways of decreasing this number. The first one is simply to reduce the amount of vehicles on the road, but as the world's population continues to increase and the number of individuals that have financial means to own private passenger vehicles grows every year; the other possibility, to decrease energy consumption of the vehicles and thereby the amount of GHG they emit, might seem like a more straightforward approach.

According to the Kyoto protocol all members of the industrialized world are committed to reduce GHG emission to at least 5% below their 1990 measurements in the years 2008 – 2012 (United Nations, 1998).

The World Business Council for Sustainable Development (WBCSD, 2001) states that 95% of all vehicles are contingent upon petroleum, with 47% running on gasoline and 31% on diesel. Passenger vehicles account for 44.5% of these vehicles (IEA, 2006).

A large part of the world is still underdeveloped and the number of vehicles per citizen is relatively low as opposed to Western Europe and USA, but as income rises in these economies the number of vehicles increases (WB, 1996). As people get wealthier they find it more desirable to own private vehicles and the car is considered a social status. When economies grow, people want faster and more powerful ways of transportation and move away from walking and bicycling towards driving and owning cars. People also have a tendency to increase the number of vehicle-trips taken as their income rises and it has been measured that in Western-Europe those trips count for around 50% of all trips taken and in the US they account for 90% (WBCSD 2002).

The WBCSD expects the transportation sector to expand, especially in growing economies such as India and China, since economic growth and transportation are related fields. As development increases the need for transportation follows along. The WBCSD notes that cities in the world have expanded and grown much faster than the population, which means that they have become more sprawled than they used to. This presents a problem of distance, since people now live further from their workplace and for that reason there has been an increase in passenger vehicles all over the world. Over 40% of people in underdeveloped countries and 75% of people of the industrialized world now live in urban areas (WBCSD 2002). The WBCSD also notes that public transportation has some difficulties in providing the services needed in wealthier societies, since mobility-related needs seem to differ in economically different societies. They find that as income reaches a certain point, i.e. where GDP per capita goes close to US$5,000/year, public transportation manages to sustain the expanding request for mobility. But when reaching this point the privately owned vehicle becomes a more noticeable option and when moving beyond this point public transportation use tends to fall and private vehicle ownership increases.

According to Lutsey and Sperling (2005) energy efficiency has improved steadily since 1975 in light-duty vehicles, but as vehicles have become larger and heavier in the U.S. during the last 20 years, fuel economy of private vehicle transport has not improved much. Instead of using the technological improvements in engine energy efficiency for public interests, such as reduced oil imports and greenhouse gas emission, it has been used to satisfy private desires like more engine power, larger vehicle size and added amenities (Lutsey and Sperling, 2006).

In Iceland, goals regarding GHG reduction were stated in a report issued by the Ministry for the Environment in 2007, stating that by 2050 Iceland's net CO_2 emission shall be 50 – 75% below the 1990 levels. The report states that in 2004 transportation accounted for 19% of the total GHG emissions. This sector has great potential for reduction by switching from the current fuel source to domestic fuels such as electricity, hydrogen, or methane (Ministry for the Environment, 2007).

The passenger vehicle fleet in Iceland continues to grow. In 2006, the number of passenger vehicles was 197.305 whereas the population at and over 18 years of age (required for obtaining a unrestricted driver's license) was 211.194 (Statistics Iceland, 2009). This yields an average of 930 vehicles per 1000 people. Most of these vehicles use imported fuel, such as gasoline and diesel (see Table 1).

In order to shed light on how to reduce the total fuel consumption of the vehicle fleet in Iceland, and thereby reducing the total GHG of the sector, the goal of this project is to find the fuel and technology that has the best efficiency and tank-to-wheel impact. Data is gathered during winter and spring in Iceland from vehicles equipped with tachographs and fuel consumption is also recorded. The fuel consumption is analyzed as a function of factors such as driving behavior, fuel source, vehicle type etc. The statistical model used helps evaluate the efficiency of the fuel used.

To summarize, the objectives of the study are:

- To collect data from different vehicles in Iceland that are propelled with various kinds of fuel.

- To identify the difference between the fuel consumption of vehicles operating on common and alternative fuels.

- To identify the effect of driving behavior and vehicle characteristics on fuel consumption.

2 Literature Review

Drive-train technology and vehicle fuel efficiency has been tested in numerous ways, including laboratory tests, simulation software, and real world driving tests.

Currently, the procedure for European Union (EU) vehicle approval is based on laboratory driving cycles. The New European Driving Cycle (NEDC), which is the EU-type approval procedure, consists of four Emission Test Cycles (ECE 15 cycles), a test cycle that is performed on a chassis dynamometer used in Europe for certifying light duty vehicle emissions standards (also known as the Urban Driving Cycle, or UDC) and one Extra Urban Driving Cycle (EUDC), which simulates highway driving conditions (Villiatico and Zuccari, 2008). These tests do not necessarily reflect real behavior of vehicles operating under normal conditions, especially when driving in urban areas (Burgess and Choi, 2002; Grugett, 1979; NAVC, 2000; Sjödin and Lenner, 1995; Tzirakis et al. 2006; Villiatico and Zuccari, 2008). There are several reasons for this. The NEDC is based on data from traffic in Paris and Rome and doesn't necessarily apply to all other cities in Europe (Tzirakis et al. 2006). Sjödin and Lenner (1995) also believe that the reason for this is that the data used in the laboratory does not represent all vehicles on the road but only a small sample of vehicles.

In a study by Grugett (1979), fuel consumption tests were applied to a 1976 Mercury Montego and were the first tests to measure wheel torque and vehicle speed, which are sufficient to calculate the work done by the vehicle. The work was divided by the fuel consumption of the vehicle to find the vehicle efficiency. These on-road data were then used in comparison with dynamometer runs and showed that the vehicle used 34% more fuel in real traffic than what was observed in the laboratory for the same amount of work. The difference is explained by different temperature. Technology has changed since then, which is demonstrated in an experiment done by Villiatico and Zuccari (2008) where a EURO 4 vehicle (Honda Civic 2000 16V) and a hydrogen modeled vehicle were compared using real vehicle data from the Honda in an urban area. The Honda was tested on the road with onboard Comprehensive Trip Log (CTL) equipment, measuring the engine's parameters that characterized its working conditions and linked to a Global Positioning System (GPS) and a Wi-Fi interface that allowed communication with the vehicle within a 100 m radius. The EURO 4 vehicle showed a 3.7% worse fuel efficiency when driving on real road conditions than when measured in the ECE cycle.

The Athens Driving Cycle (ADC) was developed and compared to the ECE-15 and the NEDC at the Laboratory of Fuel Technology and Lubricants at the National Technical University of Athens (Tzirakis et al. 2006). Real world traffic data was collected from the Athens road network with onboard electronic equipment for two years. Software was developed to do statistical analysis of the data. Three passenger vehicles of different classifications were tested on a laboratory chassis dynamometer for comparison. The results showed that for the ADC the fuel consumption was higher in all cases in comparison to the NEDC and ECE-15 (Tzirakis et al. 2006). Similar results were found in another experiment, where five state of the art hybrid-electric heavy-duty vehicles; three compressed natural gas (CNG) busses and two diesel-electric hybrid busses, were compared to one late model conventional diesel heavy-duty vehicle. The goal of the experiment was to examine the vehicles' overall energy efficiency and emission performance and the project was lead by the Northeast Advanced Vehicle Consortium (NAVC). The results show that the in-use fuel economy is lower than the results from the dynamometer, probably because of more frequent off-cycle idling and the climate control system in use (NAVC, 2000).

Route data was collected from detailed geographical maps and a detailed geographical survey between Bristol and Bath to build a model of energy demand of car transportation in England (Burgess and Choi, 2002). The routes share the same end points so they can be directly compared. The results from the model were then compared to results from the European fuel consumption and emissions test (EuroTest) (Burgess and Choi, 2002). The results from the built model showed that compared to a windless day, energy consumption increased by 14% because of wind resistance in the Lower Bristol Road, which is fast and flat, and 5% in the Upper Bristol Road, which is hilly and has tighter speed restrictions. These results were compared to the EUDC and came out 2-3 times higher. This leads to the conclusion that the EuroTest does not provide sufficient information on key design parameters like frontal area and drag coefficient (Burgess and Choi, 2002).

Several other factors have been found to influence vehicle fuel efficiency, such as driving behavior, vehicle weight, pavement structure, pavement temperature, hybridization, and regenerative braking. A laboratory test conducted on a heavy-duty truck showed that when driving on a standard 5-mile test but with different driving behavior, the truck had different fuel economy. The driving behavior that used only 30% of the available vehicle acceleration rate performed with the least fuel consumption (Rafael et al. 2006). De Vlieger (1998) found similar results with an on-road experiment that was performed in 1995 on six three-way catalyst vehicles (TWC) and one non-catalyst vehicle in order to determine their realistic emission and fuel consumption rates. These vehicles were driven in a number of ways. Under aggressive driving in city traffic, they performed with a 40% higher fuel consumption rate than when driving under calm conditions.

EcoDriving is a special driving style that reduces fuel consumption, accident rates, and greenhouse gas emissions (EcoDrive, 2009). Three different EcoDriving instructors and 16 students performed a trial in three different locations with the goal to see if EcoDriving had an impact on emissions and fuel consumption of a vehicle. A 1998 gasoline vehicle was used, equipped with an Econen trip computer, measuring factors such as engine parameters, driving style/behavior, and position. Econen used these factors to calculate the fuel consumption for the vehicle. The students drove twice each along a 10 km route that possessed some high speed limit roads, first without the EcoDriving instructions and then again after receiving EcoDriving instructions. After the second drive, the fuel consumption was reduced by an average of 10.9% (Johansson et al. 1999).

One study showed that diesel fuelled hybrid urban busses have potential in fuel reduction and field research on the energy efficiency curve shows improved fuel economy when busses have an average speed of 15-25 km/h (D'agosto and Ribeiro, 2004).

Results from the Clean Urban Transport for Europe (CUTE) project showed that there is also a strong correlation between fuel consumption and average speed. This project consisted of an emerging drive technology, 27 first generation fuel-cell hydrogen busses that were operated on a daily basis between November 2001 and May 2006 in nine major European cities. However, in this case the system performed less efficiently at lower speed due to minimum electric current limitations. The power train efficiency was 34 – 37% and the system efficiency was found to be in the range of 36 – 41%. This project was unique because it was the first real-life monitoring of a large number of the same type of fuel-cell busses operating in the same time interval (Saxe et al., 2008).

Vehicle weight plays a substantial role in this context. Based on calculations of data from 67 models of 1999–2002 model year cars, vans, and sport-utility vehicles, a reduction of 16% in fuel use would have been attained if all vehicles would have been reduced to the lowest weight per size—size meaning the lateral distance which is needed in order to make a 180° turn (Robertson, 2006). The findings from the CUTE program also demonstrate that because of increased weight of the fuel-cell busses and the current technology limit on the fuel-cell system, the fuel consumption/km is higher than for regular diesel busses (Saxe et al. 2008).

A semi-trailer tank truck was operated in the Ottawa and Montreal regions under different kinds of highway pavement structures during the years of 1999 and 2000. Data was collected based on vehicle speed, road roughness, and roadway elevation in order to attain information on the effect of pavement structure on fuel consumption (Taylor et al., 2002). A multivariate linear regression analysis determined factors that influenced the variations in the fuel economy with statistical significance. The factors that were found to have the highest statistical significance when determining a vehicle's fuel economy were (in no particular order): vehicle speed, pavement structure (concrete, asphalt, composite), pavement temperature, vehicle load, road grade, and road roughness. These factors can explain 55 – 60% of the variation in fuel consumption. As pavement temperature decreases, the fuel consumption for a vehicle with a full load—when driving at 100 km/h—increases. This applies to all pavement types. On the concrete road, the fuel consumption went from 35.8 l/100 km at 35°C up to 42.8 l/100 km at -10 °C. During highway speeds with a 25% increase in rolling resistance between asphalt and the concrete, a 5 – 6% change in fuel economy is predicted (Taylor et al., 2002).

Regenerative braking increases fuel efficiency by recapturing energy that otherwise would be lost (Folkesson et al. 2003; D'agosto and Ribeiro, 2004). In urban traffic conditions—where the speed never exceeds 50 km/h—a fuel saving of at least 20% can be expected for diesel hybrid electric vehicle (HEVs) busses, largely because of the regenerative braking (D'agosto and Ribeiro, 2004). Folkesson et al. (2003) believe this number to be even higher. Several standard duty cycles were performed on a Scania series Hybrid Proton Exchange Membrane (PEM) Fuel Cell Concept bus in Sweden and the data collected showed that the fuel consumption of the bus was 42 – 48% lower than the consumption of a standard Scania bus. The net efficiency of the fuel-cell system was around 40% and the regenerative braking recovered 28% of the energy (Folkesson et al., 2003).

Hybrid vehicles are best suited for low power demand driving when judged on their efficiency, performance, and emissions ratings according to Johansson and Áhman (2002). They compared the energy efficiency, emission, and cost of battery-powered electric vehicles (BPEVs), fuel-cell electric vehicles (FCEV), HEVs, and internal combustion engine vehicles (ICE) based on different calculated sources of data assuming the same relation between urban and rural energy use on the BPEVs, HEVs and FCEV. The results give an indication of which future technologies will compete in a carbon neutral transportation system. They found that there is a possibility of doubling the primary energy used today without added petroleum by introducing more vehicles with electric drive-trains into traffic (Johansson and Áhman, 2002). Research by the NAVC (2000) supports that by revealing that both of the diesel-electric busses that were involved in their experiment stand out in fuel consumption.

Saxe et al. (2008) suggest that by converting a vehicle to hybrid fuel technology that a certain amount of power could be recovered. In the case of the hydrogen technology, hybridization would also involve a reduction in the fuel-cell system which would decrease vehicle weight. The idle time for urban busses consumes much of their operation time and this state should be operated barely without fuel. It is concluded that by hybridization, the potential for fuel savings is large and Sisiopiku et al. (2006) agree with this. In Sisiopiku's et al. (2006) study, an Argonne National Laboratory's Power train System Analysis Toolkit (PSAT) vehicle simulation model was used to analyze various kinds of hydrogen-fuelled vehicles with available models and data, and compared with baseline conventional vehicles. The results showed that by hybridizing the vehicles, both the hydrogen and the conventional ones, there was a considerable possibility for substantial fuel economy gain. They found that a hybridized hydrogen vehicle with an internal combustion engine can achieve fuel efficiency comparable to a hybrid gasoline vehicle. The driving cycles used for vehicle testing were the Highway Fuel Economy Driving Schedule (FHDS), the aggressive driving cycle (US06), the urban route cycle (FUDS), and the combined cycle (including UDDS and FHDS).

A multi-criteria comparison of existing and under-development drive-trains was conducted by using Data Envelopment Analysis (DEA) and information from 15 different kinds of ICE, HEV, and FC vehicles running on gasoline, hydrogen, compressed natural gas, diesel, and methanol (Brey et al. 2007). The results show that some hydrogen fuel-cell vehicles, as well as other developing technologies, can be considered efficient when viewed in an environmental way. When compared on the economic criteria, vehicle retail price and fuel cost, the ICE gasoline vehicles stand out in performance but when the environmental part is taken under consideration these vehicles drop in performance and the FC vehicles overtake them (Brey et al. 2007).

One study used state-of-the-art travel survey techniques using GPS to gather 227 full day real-world driving cycle information on midsize, conventional, HEVs, and PHEVs. The vehicle performance data was then simulated over the driving profiles to evaluate and compare the laboratory data with regards to the real world data. In the real world data set, the driving was more aggressive but the PHEVs showed a 50% better fuel economy than the conventional vehicles (Gonder et al. 2007). From Villiatico and Zackary's (2008) research on the comparison between the Euro 4 vehicle and the hydrogen modeled vehicle, the results showed that the EURO 4 average efficiency with real road conditions was 18.1%, whereas the hydrogen vehicle performed with a 42.9% average efficiency. When tested under the ECE cycle, the EURO 4 had an efficiency of 21.8% and the hydrogen vehicle 47.9% (Villiatico and Zuccari, 2008). The results from Sisiopiku et al. (2006) also showed that fuel-cell hydrogen vehicles have worse fuel economy than the ICE hybrid electric vehicle, which performs with similar efficiency as the fuel-cell HEV. It is concluded that hybrid vehicles are best suited for low power demand driving when judged on their efficiency, performance, and emissions ratings (Sisiopiku et al. 2006).

Because of the various elements that influence fuel efficiency, the results differ and that leads to another controlling factor which is geographic, i.e. where globally the fuel is used and from where it has been imported. When comparing efficiency between HEVs and FCVs it is important to compare their well-to-tank (WTT) efficiency and their tank-to-wheel (TTW) efficiency, which in total adds up to their overall well-to-wheel (WTW) efficiency (Williamson and Emadi, 2005). Kreith et al. (2002) agree with this and found that it is essential—in order to compare different transportation options to each other on fair and accurate ground—to conduct a complete Well-to-Wheel fuel cycle analysis. In their research, different types of vehicles were compared to each other. Kreith et al. (2002) found that in the year 2002, HEVs using diesel components, in comparison with available technologies using natural gas for primary energy, achieved the highest efficiency, and because of poor fuel production efficiency, hydrogen ICE, electric vehicles, and methanol FCV have the lowest WTW efficiency (Kreith et al. 2002).

This though seems to be debatable. A life-cycle assessment (LCA) of the energy, environmental, and economic impacts of 10 fuel-cell vehicles with different kinds of fuel systems with regards to the WTW process was conducted in China. With regards to the geographic region of the study and the timeframe; methanol FCV showed the best results from the LCA, but pure hydrogen and gasoline also showed good potential as a short-term solution (Wang et al. 2005).

Another study compares the life-cycle of gasoline, diesel, compressed natural gas, and ethanol FC-ICE using a gasoline fuelled 1998 Ford Taurus as the baseline vehicle (MacLean et al. 2000). The other fuels and power train combinations were optimized in order to make the vehicles comparable to the Ford Taurus with regards to range, emission level, and vehicle lifetime. Input-output lifecycle analysis software (EIO-LCA) was used and the data was based on published model results. The results indicate that compared to current status in gasoline vehicles, both with regards to prices and infrastructure, alternative fuels will not easily become dominant on the market. Diesel engines are found to be attractive with regards to energy efficiency but worries rise whether they can fulfill stringent emission standards (MacLean et al., 2000).

The American Tour de Sol (ATdS), a several-hundred mile road-rally for EVs and HEVs under various driving conditions, provides a collection of road energy efficiency data that is comparable with gasoline vehicles driving under the same conditions. Three conventional gasoline vehicles (GM Saturn, Suzuki Swift, and Dodge Caravan) were compared to three electric vehicles (GM purpose-built electric two-passenger vehicle (NiMH), Solectria NiCad Force, and EPIC Minivan (NiMH)), and one hybrid electric vehicle (Honda Insight HEV (NiMH)) after the 2000 race (Patterson et al. 2000). These vehicles were driven for four days and the data was converted to British Thermal Units (BTUs). Alongside the driving data, the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model was used to estimate the total fuel cycle ramification. The results indicate that EVs and HEVs show great fuel savings potential in city driving that is characterized by stop and go driving. The combined data and GREET output give a well-to-wheel analysis and show that the HEVs that drove in the ATdS would be able to reduce full cycle oil use by approximately 56% and the EVs by over 98% in comparison to conventional gasoline engines (Patterson et al. 2000).

These studies give insight into fuel efficiency research and the influential factors that determine energy consumption. To the author's knowledge, no real life study has been performed on various vehicles, using different types of fuel and technology, in similar regional contexts. The present study compares several different alternative drive-trains, over the same period of time, in a harsh climatic setting (Reykjavik, Iceland). This study should yield new insights into the performance of emerging technologies in real traffic.

3 Empirical Setting

The vehicle fleet in Iceland has increased a great deal during the last two decades, as well as the sector's total GHG emission, and thereby follows the overall trend in the world. It is important to map out this increase, when finding means to reduce vehicles' total energy consumption and output, in order to evaluate how much reduction could take place, though that will have to be left for future research. The following chapter outlines the development in the transport sector for Iceland.

The private vehicle fleet in Iceland has grown by 32% since 2000 and by 30% in Reykjavík alone (The Road Traffic Directorate, 2010). There were 666 passenger cars registered on every 1000 citizens in Iceland in the year 2007. Only Lichtenstein and Luxemburg rate higher in Europe and in 2005 within the European Economic Area (EES 32) there was an average of 460 passenger cars for every 1000 citizens (Davíðsdóttir et al., 2009). Davíðsdóttir et al. (2009) published extensive information on the Icelandic vehicle fleet in 2009. At that time, 238,149 vehicles (passenger cars, busses, vans, trucks) were registered in Iceland, 141.188 of them located in Reykjavík. Of these, 108,978 used gasoline and 31,675 diesel. The use of alternative energy was reflected in 378 twin gasoline/electric vehicles and 7 vehicles that used only electricity. Since the year 2000, 147 methane vehicles have been registered in Iceland (these are officially categorized as diesel vehicles). In all, 21 hydrogen vehicles have been registered in Iceland since the first was registered in 2003.

Table 1 Vehicles in Iceland and Reykjavík from 2000 – 2009, in total and classified by energy source

	All vehicles		Gasoline		Diesel		Electricity	
Year	Iceland	Reykjavík	Iceland	Reykjavík	Iceland	Reykjavík	Iceland	Reykjavík
2009	238149	145999	176040	108978	61420	31675	11	7
2008	243516	176584	180977	113286	61877	32182	10	6
2007	240551	174120	181938	133219	58093	42895	10	6
2006	272905	157504	190890	130020	60964	32279	32	23
2005	254857	126951	182386	121261	53735	26115	16	11
2004	200224	118557	163294	106971	36870	19924	9	5
2003	189813	125751	156019	100624	33735	17879	9	5
2002	215769	112803	158936	100530	42122	17605	14	9
2001	181566	112803	151187	96822	30346	15952	10	6
2000	180041	112650	151131	97381	28880	15243	0	0
Increase	58108	33349	24909	11597	32540	16432	-	-
%	32%	30%	16%	12%	113%	108%	-	-

(Source: The Road Traffic Directorate, 2010)

Table 2 categorizes the number of new registrations of alternative energy vehicles per year and their energy source.

Table 2 New registrations of alternative energy vehicles in Iceland 2000-2009

Year	Gasoline/ electricity	Gasoline/Methane	Methane	Hydrogen
2009	19	4	5	1
2008	123	1	36	2
2007	161	0	43	11
2006	137	0	13	0
2005	59	0	4	0
2004	17	0	2	0
2003	1	0	1	3
2002	1	0	21	0
2001	6	0	2	0
2000	1	0	20	0
Total	525	5	147	17
Pct. of veh. fleet	0.22	0.002	0.06	0.01

(Source: The Road Traffic Directorate, 2010)

According to Davíðsdóttir et al. (2009), the share of transportation in greenhouse gas (GHG) emissions in Iceland increased from 17.8% (1990) to 22.7% (2007). This number includes domestic air travel (2%), coastal navigation (6%) and road transportation (92%). GHG emissions from transportation increased by 67% from 1990 to 2007 (from 608,000 to 1,017,000 ton CO_2 equivalence). Emissions from road transportation alone increased by 81%. By adopting various energy-saving means, emissions from transportation may decrease by 8 – 17% in 2020 and by 18 – 46% in the year 2050 (Orkuspárnefnd, 2008).

The city of Reykjavík has put together working groups to help decide the future in fuels for transportation in the city. The consensus is that the city should utilize local energy sources and strive to become sustainable in energy production and usage. Methane, electricity, and hydrogen are potentially good options for Icelandic society (City of Reykjavík, 2009).

Reykjavík has more petrol stations per capita than most cities in neighboring countries; with one station per 2,700 persons, or a total of 44 stations. In Helsinki, Finland, there are 6,000 people per station and in mainland Europe the ratio is commonly 25,000 persons per station (City of Reykjavík, 2009). Reykjavík has two hydrogen stations and one methane station (New Energy, 2010; Metan, 2010). All the oil companies in Iceland take part in implementing alternative fuels for vehicles. Olis hf. is responsible for the distribution of ethanol, Skeljungur (Shell) has played a significant role in introducing hydrogen, and N1 (Esso) runs the methane station and is a partner in Metan hf, a methane producer. The city has supported electric vehicles and contributed to recharging stands around the city that provide free electricity to vehicles (City of Reykjavík, 2009).

4 Methodology

4.1 Problem Statement/Solution Approach

The goal for this research is to decrease GHG emission from the transport sector in Iceland. Globally, the number of personally owned vehicles has increased rapidly during the past 20 years and Iceland has experienced that trend. As a result, the emission from transport has increased as well and that might have unpredictable consequences on the world's ecosystems. As an attempt to resolve this issue, the focus of this study is to find means to reduce the total emission from the vehicle sector. To do this, data that was collected from vehicles in Iceland propelled by various types of fuel during the fall of 2009 – spring 2010, was statistically analyzed. The objective is to identify what factors influence the fuel consumption of the vehicles. Knowing those factors can help to decrease emissions from vehicles in general. Another objective is to shed light on which factors are important to consider when trying to influence the energy composition of the future vehicle fleet in Iceland.

4.2 Data Collection

A vehicle fleet was selected to represent various alternative fuels (gasoline, diesel, methane, hydrogen). To collect data about the vehicle fleet's fuel consumption and driving behavior a tachograph was used from SAGAsystem™. This company was founded in 2000 in order to further develop and market the patented "Driver Assessment Program" or DAP, which is an online vehicle fleet management system based on the analysis of data collected from tachographs in vehicles.

In March 2009, an agreement was made with SAGAsystem™, selected businesses, and private car owners to get access to tachograph data from vehicles in real life operation. The tachograph gives information about distance driven and driving behavior (speed, acceleration, braking, idling, etc.) via GPS coordinates that are submitted every 2 seconds.

Key data is the fuel usage. The only way to record fuel usage in this study was to measure the amount of fuel purchased to fill the vehicles' fuel reserves since the last refill, and use the tachograph to measure the distance travelled during this refill period.

The fuel refill amount is measured in two ways; some vehicles are equipped with fuel cards that provide digital data about each refill. For other vehicles, fuel usage is recorded manually by the drivers using a refill form developed for this study (see Table 3 Refill journal for drivers). The private car owners and one business used this form.

Table 3 Refill journal for drivers

Driver	Male	Female	Age		
Post	Garbage	Bus	Private	Other	
Manufacturer	Vehicle Make	Model Year	Car no.		
Electric	Hybrid	Methane	Hydrogen	Gasoline	Diesel
Studded tires	Winter tires	Summer tires			
Refill:					
Date			Date		
Time			Time		
Temperature			Temperature		
Km read			Km read		
Amount fuel and unit			Amount fuel and unit		
Cost			Cost		
Date			Date		
Time			Time		
Temperature			Temperature		
Km read			Km read		
Amount fuel and unit			Amount fuel and unit		
Cost			Cost		
Date			Date		
Time			Time		
Temperature			Temperature		
Km read			Km read		
Amount fuel and unit			Amount fuel and unit		
Cost			Cost		
Date			Date		
Time			Time		
Temperature			Temperature		
Km read			Km read		
Amount fuel and unit			Amount fuel and unit		
Cost			Cost		

The national vehicle registry, Ekja, is used to get technical information for each vehicle (weight, power, etc.).

In addition to this data, a trip journal was developed. The drivers recorded factors such as the number of passengers, extra cargo, temperature, road conditions (asphalt, gravel, snow), and the usage of the heating/cooling system of the vehicles for each trip.

In order to obtain statistically significant results, at least 10 fuel refills were gathered for each vehicle and energy type. The study period was set from September 2009 until March 2010. This period was thought sufficiently long for all the vehicles (or vehicle groups) to need at least 10 refills. The company that hosts the tachographs and fuel data stores 3 months worth of data for each vehicle, so the data needed to be collected in November 2009 and in March 2010.

At the end of the data collection period, the data from the tachographs, the fuel monitor device, and the technical data for each vehicle were combined for statistical analysis.

4.3 Analytical Methods

When modeling a linear-in-parameters relationship between a continuous dependent variable and one or more independent variables, linear regression can be applied (Greene, 2003: Washington et al., 2003). Taylor et al. (2002) successfully applied it to model fuel consumption as a function of various explanatory variables. The basic structure of the model is:

$$y = \alpha + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + ... + \beta_n x_n + \varepsilon, \qquad (1)$$

where y is the dependent variable, a function of the constant α (the intersection of the Y-axis) and $x_{1,2,3...n}$, the independent (explanatory) variables, β (the slope of the line) are the parameters which describe the total effect of each independent variable on the dependent variable and ε is an unobserved, normally distributed error term (Greene, 2003; Washington et al., 2003). The error term describes many factors, such as omitted variables, measurement errors in the dependent variables, imprecision when measuring y and random variation inherent in the underlying data-generating process (Greene, 2003; Washington et al., 2003).

There are two possible ways of modeling the fuel consumption as a linear regression. One is to model the fuel efficiency, which is the fuel consumption per kilometer driven, as a function of explanatory variables. The other is modeling fuel consumption in kWh directly as a function of explanatory variables including kilometers driven. Both methods will be explored and tested in this study.

The aim of this study is to examine the consumption of different vehicle fuels available in Iceland, in order to see whether one type of fuel stands out in efficiency measurements. Several factors could affect the fuel consumption of the vehicle, i.e. driving style, vehicle weight, engine size, engine power (kW), etc. By gathering information about the vehicle along with fuel consumption and data from the tachograph, the influence of each of the factors can be determined by linear regression, where fuel consumption becomes the dependent variable and the rest are independent variables, that are either causing or associated with the dependent variable.

For this study, y is the fuel consumption and the independent variables are observed variables such as driving style, technical information regarding the vehicles, and distance travelled.

The method used for estimating the parameters in (1) is the Ordinary Least Squares (OLS) method, where the parameters are found by minimizing the sum of squared differences between the actual observed values and the model predictions (Washington et al., 2003):

$$\sum_{\forall i} (\hat{y}_i - y_i)^2. \tag{2}$$

For the results of a statistical analysis built on OLS to be valid, several assumptions need to hold (Washington et al., 2003). These assumptions are:

1. *The model is a linear model and the functional form is correct* (Greene, 2003; Washington et al., 2003). Equation (1) shows the functional form.

2. *The mean of the error term is zero* (Greene, 2003; Washington et al., 2003).

$$E[\varepsilon_i] = 0. \tag{3}$$

3. *The errors for different observations have the same variance (homoskedasticity)* (Greene, 2003; Washington et al., 2003).

$$VAR[\varepsilon_i] = \sigma^2. \tag{4}$$

   For each error term the same variance σ^2 must apply (Greene, 2003).

4. *The errors for different observations are not correlated but serially independent* (Greene, 2003; Washington et al., 2003). The error terms must be independent from each other.

$$COV[\varepsilon_i, \varepsilon_j] = 0, \qquad i \neq j. \tag{5}$$

5. *The independent variables and error terms are not correlated (they are exogenous)* (Greene, 2003; Washington et al., 2003). The independent variables should be exogenous (created outside of the model) and not correlated with the error. If this holds, the dependent variable, y, cannot directly influence the value of the exogenous independent variable, x, i.e. x is not a function of y.

$$COV[x_i, \varepsilon_j] = 0, \qquad \forall i, j. \tag{6}$$

6. *The error terms are normally distributed* (Greene, 2003; Washington et al., 2003). This requirement is made to allow inferences to be made about the model's parameters.

$$\varepsilon_i \sim N(0,\sigma^2)\,. \tag{7}$$

In order for the linear regression model parameters to be the best linear unbiased estimators (BLUE), that is unbiased, efficient, and consistent, these assumptions must hold (Washington et al., 2003). If these assumptions are violated it can affect the model so it becomes biased, inefficient, or inconsistent. Following are the assumption violations:

1. *The model is a linear model and the functional form is correct*. Violations: Model specification error (Washington et al., 2003). A specification error happens when the functional form is incorrect so the model becomes incorrect as well. There are four types of scenarios where this could happen:

    a. *Omitted variable bias.* A relevant variable is omitted from the specified model (underfitting a model). The correct model is demonstrated in (1). Instead, (8) represents the model being estimated,

    $$y_i^* = \alpha^* + \beta_1^* x_{1i} + \varepsilon_i^*\,, \tag{8}$$

    but if the omitted variable x_{2i} is in some way correlated with the included variable x_{1i} then both α and β_1^* become biased because the bias is a function of the covariance between the included variable and the omitted one, see (9) (Washington et al., 2003):

    $$\hat{\beta}_1^* = \beta_1 + \beta_2 \frac{COV(x_1, x_2)}{VAR(x_2)}\,. \tag{9}$$

    For the models in this study, there are several omitted variables that weren't measured, such as weather, pavement structure, etc. Omitted variable bias only occurs when the covariance between the omitted variables and the independent variables is different from zero. It is thought unlikely that the unobserved factors have such a correlation with the included data and therefore the coefficients should be unbiased.

    b. *Irrelevant variable inefficiency*. An irrelevant variable is included in the model, overfitting a model. Imagine that (10) shows the correct model,

    $$y_i = \alpha + \beta_1 x_{1i} + \varepsilon_i\,, \tag{10}$$

    but (11) is estimated instead,

    $$y_i^* = \alpha^* + \beta_1^* x_{1i} + \beta_2^* x_{2i} + \varepsilon_i^*\,, \tag{11}$$

    where the variable x_{2i} is irrelevant. This could suggest that the restriction $\beta_2^* = 0$ had not been considered. Because $E(\beta_1^*) = \beta_1$, the OLS parameters for the false model are unbiased and consistent, but inefficient because of the missing information about $\beta_2^* = 0$ (Washington et al., 2003).

All included variables for the models in this study can logically affect fuel consumption and variables with an effect not statistically significantly different from zero will be restricted to zero.

c. *An incorrect functional form for the model is applied.*

$$LN(y_i) = \alpha^* + \beta_1^* LN(x_{1i}) + \beta_2^* LN(x_{2i}) + \varepsilon_i^* \quad . \tag{12}$$

In this instance, the parameters are biased and inconsistent (Washington et al., 2003), e.g. by estimating a logarithmic model without logarithmic transformations or vice versa.

A series of tests will be performed on the variables in this study in order to capture a proper functional form. These tests are described in a later section in this Chapter.

d. *Multicollinearity*. The independent variables are highly correlated. If the correlation is high to extreme, the parameters remain consistent and continue to be BLUE, but their standard errors are disproportionately large. This makes the reliability of the estimates hard to obtain and therefore counterintuitive parameter signs become frequent. This can be observed readily when adding or removing an affected independent variable from the model as it will typically result in large changes in the size and direction of the other correlated independent variables (Washington et al., 2003).

Variables with perfect multicollinearity will not be used simultaneously. It will be tested if variables have correlation resulting in multicollinearity problems. For example, by noting sign changes in the model when a new variable is added, indicating model instability due to multicollinearity.

2. *The mean of the error term is zero*. Violation: Non-zero mean of the error term. This can e.g. happen when errors of measurements in the dependent variable are systematically biased. When this happens, (3) becomes:

$$E(\varepsilon_i) = \mu , \tag{13}$$

and causes a shift, or bias, in the constant. This changes the constant from α to $\alpha^* = \alpha + \mu$. This error only affects the intercept term α and not the slope β. But if α is omitted from the model, the coefficients β become biased and inconsistent (Washington et al., 2003).

3. *The errors for different observations have the same variance (homoskedasticity). Violation: Heteroskedasticity*. The variance is not constant across observations, that is, the error terms have a non-constant variance.

$$E(e_i^2) = \sigma_i^2 , \quad i = 1,2,...,n . \tag{14}$$

When this happens the OLS estimates are no longer efficient, but remain unbiased and consistent (Washington et al., 2003).

This study uses refill periods of varying length in time and if variables are used that are averages over the period, their standard errors would be affected and this in turn would show in the error term. However, this study will be based on total fuel consumption and a measure of the size of the refill period, the distance driven, is included.

4. *The errors for different observations are not correlated (serially independent). Violation: Serial correlation*. When disturbances from different observations are correlated the error is called serial correlation, i.e. the same driver results in several observations, several drivers are from the same company and this can create a correlation between them. The OLS estimates are no longer efficient, but still unbiased and consistent (Washington et al., 2003).

   For this data set there are multiple observations from the same vehicles and sometimes the same drivers, but the drivers do not always drive the same vehicle. Repeated observation for each vehicle will be correlated and the same applies for each driver. This can be controlled to some degree with the use of fixed effects, which is a variable that is one if it is within a predefined category and zero otherwise, and by making sure that the data from each category are not overlapping. This is done with the vehicle/fuel types and should capture this effect to a useful extent.

5. *The independent variables and error terms are not correlated. Violation: Stochastic X*, or endogeneity. This assumption is, aside from the correct functional form, the most important assumption to be met. The error terms must be uncorrelated with the independent variables, x. If this assumption does not hold, the parameter estimates becomes biased and inconsistent and the methods for finding and treating other violations of assumptions will fail. The results will continue to stay incorrect despite the amount of data being analyzed (Washington et al., 2003).

   This happens when a supposedly independent variable is truly created within the model, so it becomes endogenous, or dependent on the dependent variable. There are no variables that are created within the model, in this study, all variables are exogenous.

6. *The error terms are normally distributed. Violation: Non-normal disturbance in the error term.* This usually comes from measurement errors in the variables as well as unobserved parameter variations. This causes a bias in the standard errors which makes the hypothesis test invalid. The coefficient estimates remain unbiased and consistent but are inefficient (Washington et al., 2003).

   This is a standard assumption for errors. This can be investigated by exploring the distribution of predicted errors. Nothing in this study indicates that the errors are not normally distributed.

The t test was used to test if the parameters were statistically significantly different from zero (Washington et al., 2003).

$$t^* = \frac{\beta - 0}{S.E.(\beta)} \quad . \tag{15}$$

Here S.E. represents the standard error of each parameter (Washington et al., 2003). For the modeling of variables, the 0.05 level of significance will be used to indicate statistical significance.

With the model results, the goodness-of-fit is indicated with the R^2 value, which indicates the percent variance in the dependent data that is explained by the independent variables. This value has the limitation that it tends to grow with the number of variables included. The corrected R^2 is therefore also presented. It corrects for the number of variables and is therefore lower than the standard R^2 value (Washington et al., 2003)

$$\text{corrected } R^2 = 1 - \frac{\frac{SSE}{n-p}}{\frac{SST}{n-1}}, \tag{16}$$

Where n is the number of observations, p is the number of parameters, SSE is the sum of squared errors (2), and SST is the total sum of squares (Washington et al., 2003).

4.4 Model Development

During model development, a number of methods are used to test for nonlinear relationships between the explanatory variables and the independent variable, fuel consumption.

The first method is to separate each numeric variable into five categories based on the mean and standard deviation such that the middle category is at the mean plus or minus half a standard deviation, width of one standard deviation, and then making two categories of width one standard deviation to each side. This allows a general non-linear shift effect and helps reveal a potentially simpler non-linear relationship, such as the natural logarithmic transformation or a second order polynomial which are subsequently tested. The relationship that leads to the highest goodness of fit is chosen.

A linear regression model will be built based on the data collected from the tachograph, fuel monitor device, and vehicle characteristics. Here the objective will be to build a linear-in-parameters function based on the variables that affect fuel consumption.

A total of seven models are built and shown in the thesis.

The first model demonstrates the basic relationship between energy consumption and the distance travelled between refills. This model is naïve, but it was important to show that the data display this fundamental relationship.

The next model tests the relationship between the vehicle/energy types and fuel consumption. This model did not take into consideration the various effects of driving behavior and vehicle characteristics, but shows in general the effect each vehicle/energy type has on the fuel consumption when omitting other factors.

The third model adds vehicle weight to the naïve model of only distance (the first model). This tests another fundamental relationship, the one between energy consumption, distance travelled, and weight. It is expected that both weight and distance should increase consumption. However, since this simple model omits vehicle-specific effect and driving behavior it is possible that an omitted variable bias will be apparent in the result.

The fourth model combines the second model, which takes into consideration the fixed effects of the vehicle/energy types, and the third model, which deals with weight. This allows the vehicle-specific fixed effects to capture omitted information, such as a relatively heavy vehicle with an efficient engine. This should result in a more accurate approach for estimating the effect of weight on the vehicles' fuel consumption. To further specify vehicle characteristics, the engine power is added to develop the fifth model.

In the sixth model the effect of driving behavior is investigated. Variables for acceleration, braking, turning and speed during the refill period are used to capture this effect. This results in a fully-specified model of notable factors that affect fuel consumption. Certainly, other factors could still have an impact, such as the usage of the heating/cooling system of the vehicle, the road surface condition, environmental temperature and condition, cargo load, preheating the engine, etc.

Upon developing a fully-specified model, based on the data collected, the t-test is used to test if each coefficient is statistically significantly different from zero at the 0.05 level of significance. Coefficients not found significant are then restricted to zero to develop the final model (model seven) of important effects.

5 Data Description

Data was collected from several vehicles, both from companies and individuals, in Reykjavík, Iceland from September 2009 to March 2010. All vehicles involved had tachographs installed. All but four vehicles had a fuel card which documented each refill. These four vehicles were two Toyota Prius gasoline and two Toyota Prius hydrogen vehicles, where the owners kept a fuel diary during the data collection period.

It turned out that the manually recorded information was unreliable. Checks on consistency between dates and trips, recorded in the trip journal revealed important inconsistencies. The manually recorded information was therefore considered unreliable and the trip journal information was discarded. Emphasis was placed on using the more reliable data that was electronically collected. The manual refill records used for four vehicles were checked for consistency and were found to be valid. These were kept, rather than using only electronic monitoring, since these vehicles were the Toyota Prius vehicles, and therefore of key interest to the study.

The companies and individuals that contributed vehicles and drivers for this project were a mail delivery company, an electric distribution company, a developer company, and private car owners.

Driving style and the influence of vehicle acceleration has been shown to considerably affect the fuel consumption of vehicles (De Vlieger, 1998; Johansson et al. 1999; Taylor et al., 2002; Rafael et al., 2006; Saxe et al., 2008). For these reasons, GPS measurements from each vehicle were analyzed, as well as fuel usage, in order to correlate driving style to fuel consumption. Another variable that has been found to increase fuel consumption is weight (Robertson, 2006; Saxe et al., 2008), so for this study technical information regarding the vehicles, such as vehicle weight, power, and engine size were gathered as well.

The study excludes the effects from temperature, tire pressure, tire type, radiator usage, preheating engine, indoor storage of vehicles, driver characteristics, weather, road type, and land use. These effects are mainly excluded because of cost of collection.

According to Grugett (1979), temperature has an effect on fuel efficiency. Temperature data were gathered, but since the dependent variable (energy used by the vehicle) is viewed during the time period between refills, the average temperature would have been used as an independent factor. When viewed on average, the temperature had little variance. In order to have taken this into account further data manipulation and data collection would be required so this will have to be left for future research.

Unfortunately information about tire pressure and tire type was not available. In order to get information about radiator usage, the drivers would have had to write down if they put on the heat or air conditioning and how much strength the system worked on for each time they turned it on. An attempt was made to gather this data, but it became obvious after a while that this is hard to obtain since the drivers usually didn't give themselves the time to write this down. Data for preheating the engine was not available and the same applied for the indoor storage of vehicles. The drivers were generally not assigned one vehicle for the whole data collection period, so driver characteristics cannot be linked to the exact vehicle at the precise time.

These factors might all contribute to a decreased fuel efficiency of the vehicles tested but will have to be saved for future research. Omitting these data might have an influence on the end result of this research and might produce biased results of estimators that are correlated with the omitted variables.

Table 5 shows a complete list of the data collected and its distribution between three kinds of fuel efficiency. The fuel efficiency was calculated as the total energy used divided by the total distance travelled between refueling each vehicle. The distribution of the fuel efficiency was examined and divided equally (equal percentage share) into three categories. The first category represents fuel efficiency ranging from 0 kWh/km – 0.96 kWh/km. The second one ranges from 0.96 kWh/km – 1.16 kWh/km, and the third from 1.16 kWh/km and up.

Each column demonstrates the number of times each variable falls into that specific fuel efficiency category and how that specific variable is distributed over all of the fuel efficiency categories. The last column shows how many total observations each variable has overall and the total frequency of that variable for the total data set.

Table 4 shows the total number of vehicles that were used for the data collection by type of energy. There were a total of 47 vehicles that had usable data for analysis. The vehicles that were monitored used either methane, diesel, gasoline, or hydrogen as fuels, and the techniques involved were regular gasoline and diesel vehicles, hybrid methane and gasoline vehicles, hybrid hydrogen and electric vehicles, and hybrid gasoline and electric vehicles. 9 of the vehicles were methane, 14 diesel, 20 gasoline, 2 hydrogen hybrids and 2 gasoline hybrids.

Table 5 shows a complete list of the data collected and its distribution between three kinds of fuel efficiency. The fuel efficiency was calculated as the total energy used divided by the total distance travelled between refueling each vehicle. The distribution of the fuel efficiency was examined and divided equally (equal percentage share) into three categories. The first category represents fuel efficiency ranging from 0 kWh/km – 0.96 kWh/km. The second one ranges from 0.96 kWh/km – 1.16 kWh/km, and the third from 1.16 kWh/km and up.

Each column demonstrates the number of times each variable falls into that specific fuel efficiency category and how that specific variable is distributed over all of the fuel efficiency categories. The last column shows how many total observations each variable has overall and the total frequency of that variable for the total data set.

Table 4 Description of vehicles

Vehicle	Model Year	Fuel	Function	Manuf. Country	Passengers	Engine Size (cm^3)	Weight (kg)	Engine Power (kW)
Ford								
Focus	1999	Gasoline	Car	Germany	4	1596	1159	74
Focus	1999	Gasoline	Car	Germany	4	1596	1159	74
Focus	2000	Gasoline	Car	Germany	4	1596	1159	74
Renault								
Cangoo	2005	Gasoline	Mail delivery	France	1	1390	1020	55
Cangoo	2006	Gasoline	Mail delivery	France	Na	1149	Na	55
Cangoo	2006	Gasoline	Mail delivery	France	Na	1149	Na	55
Skoda								
Fabia	2003	Gasoline	Car	Czech Rp.	4	1198	1135	47
Toyota								
Prius	2006	Gasoline	Car	Japan	4	1497	1313	57
Prius	2004	Gasoline	Car	Japan	4	1497	1313	57
Prius Hydrogen	2006	Hydrogen	Car	Japan	4	Na	1479	57
Prius Hydrogen	2007	Hydrogen	Car	Japan	4	Na	1479	57
Volkswagen								
Caddy Met	2007	Methane	Mail delivery	Germany	1	1984	1635	80
Caddy Met	2007	Methane	Mail delivery	Germany	1	1984	1635	80
Caddy Met	2007	Methane	Mail delivery	Germany	1	1984	1635	80
Caddy Met	2007	Methane	Mail delivery	Germany	1	1984	1635	80
Caddy Met	2006	Methane	Mail delivery	Germany	1	1984	1635	80
Caddy Met	2007	Methane	Mail delivery	Germany	1	1984	1635	80
Caddy Met	2007	Methane	Mail delivery	Germany	1	1984	1635	80
Caddy Met	2006	Methane	Mail delivery	Germany	1	1984	1635	80
Caddy Met	2006	Methane	Mail delivery	Germany	1	1984	1635	80
Caddy	2004	Diesel	Light delivery	Germany	1	1968	1390	51

(*Continued*)

Table 4 (Continued)

Vehicle	Model Year	Fuel	Function	Manuf. Country	Passengers	Engine Size (cm^3)	Weight (kg)	Engine Power (kW)
Caddy	2004	Diesel	Mail delivery	Germany	1	1968	1390	51
Caddy	2006	Diesel	Light delivery	Germany	1	1968	1390	51
Caddy	2006	Diesel	Light delivery	Germany	1	1968	1390	51
Caddy	2006	Diesel	Light delivery	Germany	1	1968	1390	51
Caddy	2006	Diesel	Light delivery	Germany	1	1968	1390	51
Caddy	2006	Diesel	Light delivery	Germany	1	1968	1390	51
Caddy	2007	Diesel	Light delivery	Germany	1	1968	1440	51
Caddy	2007	Diesel	Light delivery	Germany	1	1896	1455	77
Caddy	2007	Diesel	Light delivery	Germany	1	1968	1440	51
Caddy	2007	Diesel	Light delivery	Germany	1	1896	1455	77
Caddy	2008	Diesel	Light delivery	Germany	1	1968	1440	51
Caddy	2008	Diesel	Light delivery	Germany	1	1968	1440	51
Caddy	2000	Gasoline	Light delivery	Germany	1	1598	1060	55
Caddy	2000	Gasoline	Light delivery	Germany	1	1390	1100	55
Caddy	2001	Gasoline	Light delivery	Germany	1	1390	1100	55
Caddy	2004	Gasoline	Light delivery	Germany	1	1390	1340	59
Caddy	2007	Gasoline	Light delivery	Germany	1	1390	1340	59
Caddy	2007	Gasoline	Light delivery	Germany	1	1390	1340	59
Golf	2001	Gasoline	Car	Germany	4	1984	1423	85
Golf	2002	Gasoline	Car	Germany	4	1595	1356	75
Golf	2003	Gasoline	Car	Germany	4	1984	1472	85
Golf	2003	Gasoline	Car	Germany	4	1595	1356	75
Golf	2004	Gasoline	Car	Germany	4	1984	1472	85
Golf	2004	Gasoline	Car	Germany	4	1598	1342	77
Golf	2006	Gasoline	Car	Germany	4	1598	1342	77

Table 5 Data collected distributed between three categories of fuel efficiency

	Efficiency < 0.96 kWh/km		Efficiency 0.96 – 1.16 kWh/km		Efficiency > 1.16 kWh/m		Total	
	Freq.	**%**	**Freq.**	**%**	**Freq.**	**%**	**Freq.**	**%**
N	**682**	**100**						
Vehicle Characteristics								
Manufacturer								
Renault	2	6.67	8	26.67	20	66.67	30	4.40
Ford	18	46.15	19	48.72	2	5.13	39	5.72
Volkswagen	171	30.05	198	34.80	200	35.15	569	83.43
Toyota	30	81.08	2	5.41	5	13.51	37	5.43
Skoda	7	100.00	0	0.00	0	0.00	7	1.03
Vehicle make								
Cangoo	2	6.67	8	26.67	20	66.67	30	4.40
Focus	18	46.15	19	48.72	2	5.13	39	5.72
Caddy Gasoline	10	21.74	27	58.70	9	19.57	46	6.74
Caddy Diesel	65	63.73	20	19.61	17	16.67	102	14.96
Caddy Methane	74	22.42	98	29.70	158	47.88	330	48.39
Golf	22	24.18	53	58.24	16	17.58	91	13.34
Prius Hydrogen	29	93.55	1	3.23	1	3.23	31	4.55
Prius	1	16.67	1	16.67	4	66.67	6	0.88
Fabia	7	100.00	0	0.00	0	0.00	7	1.03
Model year								
1999	12	46.15	14	53.85	0	0.00	26	3.81
2000	9	32.14	9	32.14	10	35.71	28	4.11
2001	2	20.00	2	20.00	6	60.00	10	1.47
2002	8	36.36	14	63.64	0	0.00	22	3.23
2003	8	25.81	15	48.39	8	25.81	31	4.55
2004	29	42.65	33	48.53	6	8.82	68	9.97
2005	1	6.67	3	20.00	11	73.33	15	2.20
2006	92	61.74	56	37.58	60	40.27	149	21.85
2007	64	19.63	81	24.85	122	37.42	326	47.80
2008	3	42.86	0	0.00	4	57.14	7	1.03
Vehicle weight (kg)								
<= 1200	31	38.75	28	35.00	21	26.25	80	11.73
> 1300 <= 1399	70	49.30	51	35.92	21	14.79	142	20.82
> 1400 <= 1499	52	45.22	45	39.13	18	15.65	115	16.86
= 1635	153	45.40	124	36.80	60	17.80	337	49.41
Engine power (kW)								
47 – 59	107	52.71	49	24.14	47	23.15	203	29.77
74 -77	44	41.12	49	45.79	14	13.08	107	15.69
80 – 85	77	20.70	129	34.68	166	44.62	372	54.55

(*Continued*)

Table 5 (Continued)

	Efficiency < 0.96 kWh/km		Efficiency 0.96 – 1.16 kWh/km		Efficiency > 1.16 kWh/m		Total	
	Freq.	**%**	**Freq.**	**%**	**Freq.**	**%**	**Freq.**	**%**
Engine size (cm^3)								
1149 – 1497	19	24.36	34	43.59	25	32.05	78	11.44
1595 – 1598	38	38.38	43	43.43	18	18.18	99	14.52
1896 – 1984	171	33.86	150	29.70	184	36.44	505	74.05
Vehicle fuel								
Electricity	0		0		0		0	0.00
Methane	74	22.42	98	29.70	158	47.88	330	48.39
Hydrogen	29	93.55	1	3.23	1	3.23	31	4.55
Gasoline	59	27.70	107	50.23	47	22.07	213	31.23
Diesel	65	63.73	20	19.61	17	16.67	102	14.96
Vehicle use								
Mail delivery vehicle	77	21.10	108	29.59	180	49.32	365	53.52
Delivery vehicle	104	57.78	47	26.11	29	16.11	180	26.39
Regular vehicle	77	44.25	74	42.53	23	13.22	174	25.51
Driving Chararcteristics								
Average speed (km/h)								
<= 28.89	0	0.00	0	0.00	7	100.00	7	1.03
> 28.89 <= 41.23	51	17.53	90	30.93	150	51.55	291	42.67
> 41.24 <= 47.42	44	37.93	35	30.17	37	31.90	116	17.01
> 47.42 <= 53.61	25	49.02	12	23.53	14	27.45	51	7.48
> 53.61	108	49.77	90	41.47	19	8.76	217	31.82
Total cost of refueling (IKR)								
<= 2246	52	44.83	27	23.28	37	31.90	116	17.01
> 2246 <= 2942	25	19.69	42	33.07	60	47.24	127	18.62
> 2942 <= 3637	26	26.53	24	24.49	48	48.98	98	14.37
> 3637 <= 5028	3	10.34	7	24.14	19	65.52	29	4.25
> 5028	122	39.10	127	40.71	63	20.19	312	45.75
Stop length (minutes)								
<= 3.58	71	30.47	68	29.18	94	40.34	233	34.16
> 3.58 <= 7.63	56	27.32	68	33.17	81	39.51	205	30.06
> 7.63 <= 11.67	56	44.09	45	35.43	26	20.47	127	18.62
> 11.67 <= 19.75	29	41.43	26	37.14	15	21.43	70	10.26
> 19.75	16	34.04	20	42.55	11	23.40	47	6.89

(*Continued*)

Table 5 (Continued)

	Efficiency < 0.96 kWh/km		Efficiency 0.96 – 1.16 kWh/km		Efficiency > 1.16 kWh/m		Total	
	Freq.	**%**	**Freq.**	**%**	**Freq.**	**%**	**Freq.**	**%**
Idle (instance)								
<= 46	84	34.85	85	35.27	72	29.88	241	35.34
> 46 <= 68	62	44.60	36	25.90	41	29.50	139	20.38
> 68<= 89	39	33.05	47	39.83	32	27.12	118	17.30
> 89 >= 132	26	19.26	47	34.81	62	45.93	135	19.79
> 132	17	34.69	12	24.49	20	40.82	49	7.18
Severe Acceleration (instance)								
<= 19	59	25.54	48	20.78	124	53.68	231	33.87
> 19 <= 69	57	25.22	95	42.04	74	32.74	226	33.14
> 69	112	49.78	84	37.33	29	12.89	225	32.99
Severe Braking (instance)								
<= 1	68	25.47	62	23.22	137	51.31	267	39.15
> 1 <= 7	63	29.86	83	39.34	65	30.81	211	30.94
> 7	97	47.55	82	40.20	25	12.25	204	29.91

Stop length in minutes indicates the total time a vehicle is stopped with the engine running. Clearly this is expected to increase fuel consumption beyond distance travelled and other factors. Idling is here defined as an event when a vehicle is stopped but running for more than 200 sec, in order to omit stops at traffic signals.

As Table 5 shows, the majority of vehicles were produced by Volkswagen, or 83.43%, Toyota had a 5.43% share, Ford 5.72%, Renault 4.4%, and Skoda only 1.03%. Caddy Methane was the most frequent sub type with a percentage of 48.39%, then came the Caddy Diesel with 14.96%, and the Golf with 13.34%. Most vehicles were 2006 and 2007 models, or 21.85% and 47.8% respectfully, and 9.97% were 2004 model. Most vehicles, or a total of 49.41%, weighed around 1600 kg, 20.82% weighted between 1300 – 1400 kg, 16.86% weighted between 1400 – 1500 kg, and 11.73% between 1200 – 1300 kg.

6 Results

Fuel efficiency as fuel consumption in kWh per kilometer driven was regressed on the explanatory variables. Fuel consumption in kWh was also directly regressed on the explanatory variables including kilometers driven. The initial results showed a poor fit for fuel efficiency when regressed on the data. One explanation may be a lack of variance in the fuel efficiency variable or that the correct functional form is highly non-linear. The R^2 results for fuel efficiency models never exceeded 0.1.

Analyzing fuel consumption as a function of distance travelled, and other explanatory factors, resulted in a strong model fit. This was therefore chosen as the basis for the analysis presented in this study. One limiting issue is that the research is based on refill periods of various lengths due to different uses and different energy storage capability of the vehicles. A better way would be to dynamically monitor fuel consumption in real-time while driving, rather than estimate it based on fuel purchased and distance travelled over extended time periods of various lengths. Such an investigation is impossible within the bounds of this research.

The results from the linear regression models appear in Table 6 –Table 12. In all the models, the energy consumption (kWh) of the vehicles during one refill period is the dependent variable. The estimated coefficients are either positive or negative; if positive then a coefficient has an increasing effect on the energy consumption of the vehicles; if negative it has a decreasing effect.

Table 6 shows the simplest model (model 1, see chapter 4.4 Model Development), which demonstrates the basic relationship between energy consumption and the distance travelled in between refills. The model shows that the further the vehicles are driven the more energy they consume at the mean rate of 0.32 kWh/km. The R^2 explains that the model captures 35% of the variance of the energy consumption showing the need for additional explanatory variables.

Table 6 Relationship between Energy Consumption and Distance Travelled.

Variable	Estimated Coefficient	Std.Err.	t-statistic
Constant	268.34	8.77	30.59
Independent variable			
Distance travelled between refills (km)	0.32	0.02	18.99
N	682		
R^2	0.35		
Corrected R^2	0.35		

In Table 7 (model 2) the general relationship between vehicle/energy type and energy consumption is shown. This is useful for ranking the vehicles in terms of energy consumption. However this method is limited since it omits the actual usage pattern of the vehicles. The effect of each vehicle is relative to the omitted base case vehicle, which here is Volkswagen Golf Gasoline.

Table 7 Relationship between Energy consumption and Vehicles measured.

Va riable	Estimated coefficient	Std.Err.	t-statistic
Constant	588.70	7.38	79.75
Independent variables			
Volkswagen Caddy Methane	-323.59	8.34	-38.81
Toyota Prius Hydrogen	-537.58	14.64	-36.71
Toyota Prius Gasoline	-197.35	29.68	-6.65
Volkswagen Caddy Diesel	23.03	10.15	2.27
Volkswagen Caddy Gasoline	-0.75	12.74	-0.06
Renault Cangoo Gasoline	-212.26	14.83	-14.32
Ford Focus Gasoline	-63.28	13.48	-4.70
Skoda Fabia Gasoline	-157.17	27.62	-5.69
N	682		
R^2	0.86		
Corrected R^2	0.85		

Note: Volkswagen Golf Gasoline is the omitted base case fixed effect.

The Toyota Prius Hydrogen is ranked with the lowest energy consumption compared to the other vehicles, whereas Volkswagen Caddy Diesel has the highest. It is important now to consider the impact of other related factors such as vehicle usage and characteristics.

Table 8 (model 3) shows another simplistic model, the relationship between distance travelled, vehicle weight, and energy consumption. It can be expected in simple terms that energy consumptions is increased, the greater the distance and weight. Table 8 does not show this expectation but indicates that the heavier the vehicle, the lesser the energy consumption. This shows the danger of running a model without all appropriate explanatory variables. Such a model suffers from omitted variable bias which affects the coefficient estimates and renders the results erroneous. It can be hypothesized that there is a heavy vehicle with low energy consumption within the sample, which leads to this counterintuitive result.

Table 8 Relationship between Energy consumption, Distance travelled and Vehicle weight.

Variable	Estimated coefficient	Std.Err.	t-statistic
Constant	927.79	50.31	18.44
Independent variables			
Distance travelled between refills (km)	0.24	0.02	14.22
Vehicle weight (kg)	-0.42	0.03	-13.29
N	667		
R^2	0.49		
Corrected R^2	0.48		

In order to accurately capture the effect of weight, fixed effects are added for the vehicle/energy types into the model and this is shown in Table 9 (model 4).

Table 9 Relationship between Energy consumption, Distance travelled, Vehicle weight and Vehicles measured.

Variable	Estimated coefficient	Std.Err.	t-statistic
Constant	78.47	88.61	0.89
Independent variables			
Distance travelled between refills (km)	0.04	0.01	4.04
Vehicle weight (kg)	0.35	0.06	5.47
Volkswagen Caddy Methane	-390.24	17.55	-22.24
Toyota Prius Hydrogen	-544.37	15.89	-34.25
Toyota Prius Gasoline	-157.66	29.17	-5.40
Volkswagen Caddy Diesel	18.61	9.80	1.90
Volkswagen Caddy Gasoline	49.59	16.83	2.95
Renault Cangoo Gasoline	-83.71	30.58	-2.74
Ford Focus Gasoline	23.00	20.19	1.14
Skoda Fabia Gasoline	-67.35	31.68	-2.13
N	667		
R^2	0.87		
Corrected R^2	0.87		

Note: Volkswagen Golf Gasoline is the omitted base case fixed effect.

When vehicle fixed effects are added to the model, the weight shows the expected effect. Note that the energy consumption contribution due to distance is greatly diminished due to the fixed effects. Toyota Prius Hydrogen is ranked with the overall least energy usage when controlling only for distance and weight, but when omitting specific vehicle usage or characteristics. Volkswagen Caddy Gasoline is ranked with the highest overall energy consumption. Note that again the Volkswagen Golf Gasoline is the base case vehicle.

In Table 10 (model 5), the effect of engine power has been added to the previous model (see Table 9). This model shows generally the same results as the model in Table 9. However, the engine power has the unexpected effect that the larger the engine, the lesser the energy consumption of the vehicle. This is another sign of omitted variable bias. Greater power naturally should lead to greater energy consumption. Factors correlated with engine power are still omitted from this model, notably driving behavior.

Table 10 Relationship between Energy Consumption, Distance Travelled, Vehicle Weight, Engine Power and Vehicles Measured.

Variable	Estimated coefficient	Std.Err.	t-statistic
Constant	80.59	89.05	0.91
Independent variables			
Distance travelled between refills (km)	0.04	0.01	3.98
Vehicle weight (kg)	0.36	0.07	4.95
Engine Power (kW)	-0.18	0.69	-0.26
Volkswagen Caddy Methane	-392.39	19.39	-20.23
Toyota Prius Hydrogen	-549.30	24.69	-22.25
Toyota Prius Gasoline	-161.05	31.94	-5.04
Volkswagen Caddy Diesel	14.20	19.53	0.73
Volkswagen Caddy Gasoline	47.10	19.32	2.44
Renault Cangoo Gasoline	-84.90	30.94	-2.74
Ford Focus Gasoline	24.06	20.61	1.17
Skoda Fabia Gasoline	-70.87	34.44	-2.06
N	667		
R^2	0.87		
Corrected R^2	0.87		

The next step is therefore to account for driving behavior. Table 11 (model 6) shows the fully-specified model of energy consumption as a function of distance, weight, engine power, vehicle fixed effects, and driving behavior.

Table 11 Relationship between Energy consumption, Vehicle characteristics, Driving behavior and Vehicles measured.

Variable	Estimated coefficient	Std.Err.	t-statistic
Constant	454.11	110.17	4.12
Independent variables			
Distance travelled between refills (km)	0.08	0.015	5.27
Vehicle weight (kg)	0.078	0.08	0.97
Engine Power 77.34 - 89.67 kW	52.25	16.42	3.18
Volkswagen Caddy Methane	-457.73	39.35	-11.63
Toyota Prius Hydrogen	-517.08	37.56	-13.77
Toyota Prius Gasoline	-148.46	47.93	-3.10
Volkswagen Caddy Diesel	-16.29	43.60	-0.37
Volkswagen Caddy Gasoline	4.38	43.20	0.10
Renault Cangoo Gasoline	-236.27	46.08	-5.13
Ford Focus Gasoline	-255.57	85.49	-2.99
Skoda Fabia Gasoline	-208.21	55.77	-3.73
Severe braking events	0.41	0.30	1.35
Severe braking events Toyota Prius Hydrogen and Gasoline	-19.87	7.14	-2.78
Severe braking events Caddy Diesel	-1.24	0.55	-2.28
Severe braking events Caddy Gasoline	-3.35	0.64	-5.22
Ln (severe acceleration events)	-1.71	6.30	-0.27
Ln (severe acceleration events Caddy Methane)	15.61	7.46	2.09
Ln (severe acceleration events Ford Focus Gasoline)	30.13	17.45	1.73
Ln (severe acceleration events Volkswagen Golf Gasoline)	-15.69	9.72	-1.61
Average speed 41.2 = 47.4 km/h	26.41	7.17	3.68
Stop length (minutes)	15.35	3.32	4.62
Idle events > 89	16.29	6.75	2.41
N	657		
R^2	0.89		
Corrected R^2	0.88		

Note: Volkswagen Golf Gasoline is the omitted base case fixed effect.

In the model in Table 11, estimated coefficients are shown even though they are not statistically significantly different from zero at the 0.05 level of significance in order to show the full model. The model now shows the expected effect of the key variables on energy consumption. The distance, vehicle weight, and engine power all tend to increase energy consumption when controlling for the other factors. However, vehicle weight has been rendered not significant, likely due to the fixed effects and the driving behavior factors.

Recall that in order to find the proper functional form, nonlinear relationships were tested for all non-indicator variables (i.e. variables that are real or integer numbers). This explains the logarithmic transformation on the acceleration variables and that average speed and number of idle events are categorical variables. The categories were used to capture non-linear shift effects.

Table 12 (model 7) presents the fully-specified model after coefficients not significantly different from zero have been restricted to zero.

Table 12 Relationship between Energy consumption, Vehicle characteristics, Driving behavior and Vehicles measured with Significant Coefficients.

Variable	Estimated coefficient	Std.Err.	t-statistic
Constant	543.06	10.16	53.33
Independent variables			
Distance travelled between refills (km)	0.08	0.01	6.46
Engine Power 77.34 - 89.67 kW	58.12	13.18	4.43
Volkswagen Caddy Methane	-426.67	19.84	-21.50
Toyota Prius Hydrogen	-494.12	17.21	-28.71
Toyota Prius Gasoline	-139.34	35.20	-3.96
Renault Cangoo Gasoline	-247.97	14.79	-16.77
Ford Focus Gasoline	-289.29	76.67	-3.77
Skoda Fabia Gasoline	-203.05	25.10	-8.10
Severe braking events Toyota Prius Hydrogen and Gasoline	-20.03	6.77	-2.96
Severe braking events Caddy Diesel	-1.02	.367	-2.77
Severe braking events Caddy Gasoline	-3.07	.4268	-7.18
Ln (severe acceleration event Caddy Methane)	14.07	4.35	3.23
Ln (severe acceleration event Ford Focus Gasoline)	37.86	14.87	2.55
Ln (severe acceleration event Volkswagen Golf Gasoline)	-12.39	2.55	-4.87
Average speed 41.2 - 47.4 km/h	27.53	7.00	3.94
Stop length (minutes)	14.63	3.10	4.71
Idle events >89	17.50	6.62	2.64
N	670		
R^2	0.89		
Corrected R^2	0.88		

Note: Volkswagen Golf Gasoline is the omitted base case fixed effect. Also omitted are the Volkswagen Caddy Diesel and Gasoline, which were not found statistically significantly different from the Volkswagen Golf Gasoline.

The full model in Table 12 has a high goodness-of-fit, with the R^2 indicating about 89% of the variance in energy consumption is explained by the model. Compare this with the goodness-of-fit of the naïve models, e.g. Table 8 –Table 10

This model shows that the greater the distance, the greater the energy consumption. With all other factors being kept constant, the energy consumption grows on average by 0.08 kWh per km travelled.

The investigation of the functional form of engine power on energy consumption resulted in a non-linear fixed effect for the vehicles with the greatest engine power (77.34 – 89.67

kW) in the sample; their energy consumption is greater on average compared to the other vehicles by 57.7 kWh.

The Toyota Prius Hydrogen is found to have the lowest energy consumption of the vehicles analyzed, all other variables being kept constant. The second lowest in energy consumption by the same measure is the Volkswagen Caddy Methane. The Toyota Prius Gasoline is measured similar with the gasoline vehicles in the study. The highest energy users are the Volkswagen Golf Gasoline, Volkswagen Caddy Diesel and Gasoline which are not found statistically significantly different from each other when accounting for all other factors. It is important to highlight the limitation that fuel consumption is measured based on refill periods of various duration, with vehicles that store various amount of energy. As previously noted, an onboard fuel consumption computer that can dynamically track fuel usage would lead to more accurate results. It is not impossible that the Toyota Prius Hydrogen is measured with the lowest fuel consumption because it also has a relatively small energy container and a short refill period.

The Prius vehicles gain energy from braking and are therefore included in an interaction term with the number of braking events. The variable shows the expected effect, that the greater the number of braking events in a Toyota Prius, the lower the energy consumption. Interestingly, the Volkswagen Caddy, Diesel and Gasoline, also show such an effect, although smaller, which may explain the lack of significance of their fixed effects. This may seem counterintuitive at first sight. However, when braking, a driver is normally not also stepping on the “gas”, so braking can save energy when controlling for acceleration, which is done here. After braking, a vehicle will inevitably accelerate back up to speed which might cause braking to be linked to higher fuel consumption. But this does not occur here because acceleration is captured separately in this model.

As the natural logarithm of the total number of acceleration events increases so does the energy consumption for Volkswagen Caddy Methane and Ford Focus Gasoline. The natural logarithm was chosen after a test of non-linear forms for the variables. Unexpectedly, Volkswagen Golf Gasoline is linked with the opposite effect. This may be an artifact from the decision of choosing the Volkswagen Golf as the base case for the fixed effects. It is also possible that this is yet another case of omitted variable bias, although the high goodness-of-fit of the model in terms of R^2 indicates that by far the most of the variance in energy consumption has been explained. The effect was not significant for the other vehicles.

Average speed between 41.2 – 47.4 km/hour had an increasing effect on fuel consumption compared to higher or lower speeds. This average speed could represent typical “in city” driving, which is a mixture of acceleration and deceleration due to intersections and traffic, and thereby less energy efficient. Higher average speeds could indicate long distance driving, which involves lesser events of acceleration and better fuel efficiency. Lower average speeds indicate minimal acceleration and thereby lower fuel usage.

The largest category of idling events, representing 73 or more such events during the refill period, is associated with additional fuel consumption beyond the effect of the stop length in minutes.

7 Conclusions

The objectives of this study were to collect data from different kinds of road vehicles in Iceland that were propelled with various kinds of fuels, including the common fuels gasoline and diesel, as well as alternative fuels such as methane and hydrogen. This is done in order to identify the difference between the fuel efficiency as measured by the vehicles' fuel consumption and relate it to other factors such as vehicle characteristics and driving behavior.

Factors that were specifically under observation were the distance travelled on a measured amount of fuel (a refill period), the vehicle weight and other vehicle characteristics, and driving behavior.

A linear regression model was used to analyze the data collected in order to statistically evaluate which factors significantly influence the fuel consumption and to identify the difference between the observed variables.

The first analysis was based on a complete data collection effort using a trip diary where drivers were intended to record information about each trip, e.g. distance travelled, weather, vehicle load, etc. After gathering the data it became obvious that this data collection was unreliable and inaccurate. It appeared that drivers wrote down the information at the end of the day, or worse, at the end of the week. The data was not reliable for use.

The decision was made to attempt to use automatic recording of driving behavior using a SAGAsystem™ tachograph which collected information about driving distance, the frequency of severe acceleration events, and other related information. Fuel usage was measured using fuel cards which participants used to refill the vehicles with fuel. This digital data was found to be more reliable although there were periods where the system did not return data.

With regards to driving behavior, the primary variables that were analyzed in the study were the number of severe braking events, the number of severe acceleration events, the number of severe turning events, and average speed during the refill period.

The most notable effect on increased fuel consumption results from the severe acceleration events, but not turning and braking as one might perhaps think. This is to be expected because when the driver performs these actions (braking hard or turning sharply) the driver lets go of the "gas", so little fuel consumption takes place exactly during this phase. Braking is important when acceleration is not accounted for, since the primary fuel consumption occurs when the driver accelerates after slowing down.

The main contributor to decreased fuel consumption within this field can therefore be viewed as keeping a steady speed since no acceleration takes place when driving at a constant speed. This supports the result that acceleration is a major factor for increased fuel consumption.

Braking, however, should not be undervalued. Regenerative braking, which charges a vehicle's batteries, had an overall significant improving effect on fuel consumption. This is the case in the Toyota Prius vehicles and contributes further to their energy efficiency, beyond the estimated vehicle-specific fixed effect for these vehicles. However, future research should importantly perform a sensitivity analysis in order to fully describe the overall effect for each vehicle. The present study results in conclusions for each variable, keeping all other variables constant.

Hydrogen and methane provided the overall best results in fuel consumption when all other factors are kept constant. Here is to be noted that this research was not able to take into consideration the potential effect of the energy density of the different fuels tested. For the hydrogen vehicles, the refills take place much more frequently than for e.g. the gasoline vehicles and this might have an influence on the overall fuel consumption, since the variance in fuel consumption is potentially greater during a longer refill period.

For this research, one notable problem that occurred was the occasional interruption of the GPS monitoring device, which led to missing data in spots within a refill period, i.e. the distance travelled came up short and a naïve calculation of fuel consumption using incorrectly short distances had a great effect on the fuel consumption. This problem was resolved here by identifying these observations and removing them.

Future research could benefit from the use of an onboard fuel monitoring device, which could provide a more accurate measure of fuel consumption per kilometer as it occurs, as opposed to the method applied here, where the fuel consumption was measured during multi-day time periods that varied between vehicles.

To summarize, the key contributors to decreasing energy consumption are: To drive with a constant speed, to use modest acceleration when gaining speed, and the implementation of regenerative braking. For future research, an onboard fuel monitoring device is recommended in order to more accurately capture real-time fuel consumption during driving. The specific research results from this project show that the hydrogen and methane vehicles provided the lowest fuel consumption, when controlling for other factors and keeping them fixed. These results support the benefits of EcoDriving and could prove to have future benefits for the country if they were implemented into driving schools.

These results should be taken into consideration when developing policy or plans to decrease the total emissions from the road transport sector in Iceland.

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