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Investigation of vehicle and driver aggressivity and relation to fuel economy testing

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INVESTIGATION OF VEHICLE AND DRIVER AGGRESSIVITY AND RELATION TO FUEL ECONOMY TESTING

by

Jonathan Seth Stichter

A thesis submitted in partial fulfillment
of the requirements for the Master of
Science degree in Mechanical Engineering
in the Graduate College of
The University of Iowa

December 2012

Thesis Supervisors: Associate Professor Albert Ratner

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CERTIFICATE OF APPROVAL

MASTER'S THESIS

This is to certify that the Master's thesis of

Jonathan Seth Stichter

has been approved by the Examining Committee
for the thesis requirement for the Master of Science
degree in Mechanical Engineering at the December 2012 graduation.

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ABSTRACT

As vehicle technologies continue to improve it is becoming more evident one of the last major factors impacting fuel economy left today is the driver. In this study the driver is defined as the operator of a vehicle and the difference between driving styles of the driver and vehicle is defined as aggressivity. Driver aggressivity is proven to have a substantial impact on fuel economy in many studies. Many fuel economy tests have been created, all to measure the fuel efficiency of today's vehicles and their related technologies. These tests typically require that the drivers be trained or experienced in fuel economy testing unless the impact of the driver on fuel economy is the variable being tested. It is also recommended, for certain tests, that the driver stay with the same vehicle for the tests entirety. Although these are the requirements, having the same trained drivers for the entirety of a fuel economy test may not always be a viable option. This leads to the question of, what impact can a set of drivers, who are asked to drive the same, have on fuel consumption during a fuel consumption test? The SAE J1321 Type II Fuel Consumption Test Procedure was followed on two identical trucks with two drivers that were untrained in fuel economy testing in order to answer this question. It was found in this particular study that the driver variability can impose up to a 10% fuel economy difference on shorter distance routes where the driver is kept the same. By increasing the distance of the route and swapping drivers variability in fuel economy reduced to 5%. It was shown by this particular test that the impact of the driver when asked to drive the same is minimal compared to real world results of up to 30%. A larger data set and more testing is still necessary to completely understand and validate the impact of the driver on fuel economy testing.

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CHAPTER 1: INTRODUCTION

1.1 Background and Literature Review

As vehicle technologies continue to improve it is becoming more evident one of the last major factors impacting fuel economy left today is the driver. In this study the driver is defined as the operator of a vehicle and the difference between driving styles is aggressivity. Aggressivity for this study, which will be defined in further detail, can be summarized as the variance between how different drivers and/or vehicle accelerate and decelerate. Driver aggressivity is proven to have a substantial impact on fuel economy in many studies. Fuel economy is a measure of how many miles a vehicle can travel on one gallon of fuel which is abbreviated mpg. Many fuel economy tests have been created, all to measure the fuel efficiency of today’s vehicles and their related technologies. These tests typically require that the drivers be trained or experienced in fuel economy testing unless the impact of the driver on fuel economy is defined as the goal of the test. It is also recommended, for certain tests, that the driver stay with the same vehicle for the tests entirety. Although these are the requirements, having the same drivers that are also trained for the entirety of a fuel economy test may not always be a viable option. This leads to the question of, what impact a driver can have on fuel consumption during a fuel consumption test.

As stated above, many studies have been done on the effect the driver can impose on fuel economy. The results of these studies show that different driving styles and behaviors can have correlating impacts on the amount of fuel used in the same vehicle on the same drive cycle. Many light duty automotive studies on driver aggressivity have been done including one by the National Renewable Energy Laboratory (NREL). NREL took on the task of better understanding what improvements can be made to fuel economy by changing driver behavior. It was found that more efficient driving behavior could reduce fuel use by as much as 20% on more aggressive stop and go drive cycles. If a driver is considered moderate in their driving style, an improvement anywhere from 5-10% can be seen.

Figure 1-1 shows a 30% spread between the lowest fuel consuming energy conscious repetition and the highest fuel-consuming aggressive repetition on a city route. The apparent correlation between fuel consumption differences and characteristic acceleration is consistent with other findings in the paper that reducing acceleration and deceleration seem to carry the largest benefit in city-type driving with significant stop or slow and go events. (Gonder 2012)

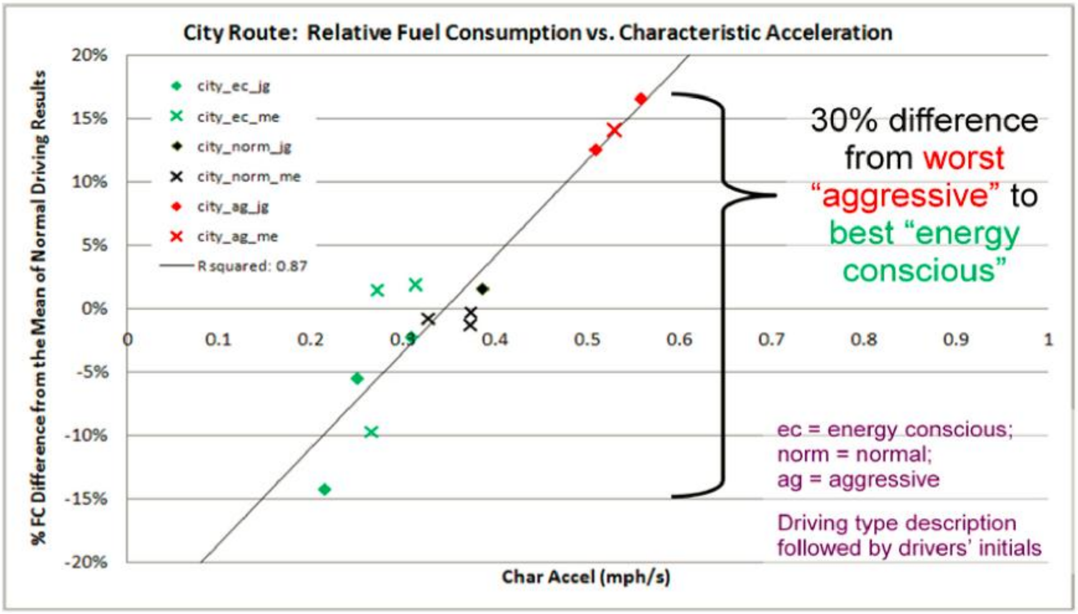


Figure 1-1: Fuel Use Comparison For "City" Driving Experiments.

Source: Gonder, J., Earleywine, M. and Sparks, W., "Analyzing Vehicle Fuel Saving Opportunities through Intelligent Driver Feedback," *SAE Int. J. Passeng. Cars - Electron. Electr. Syst.* 5(2):2012, doi:10.4271/2012-01-0494.

For highway driving cycles NREL showed that vehicle speed had a greater impact on fuel economy. This correlation is due to the exponential impact that aerodynamics has on fuel consumption with respect to speed. Higher speeds correlate to more fuel consumed. At the lower speed city driving cycles, aerodynamics does not play as crucial of a role. The correlation of speed to fuel consumption can be seen in Figure 1-2 below.

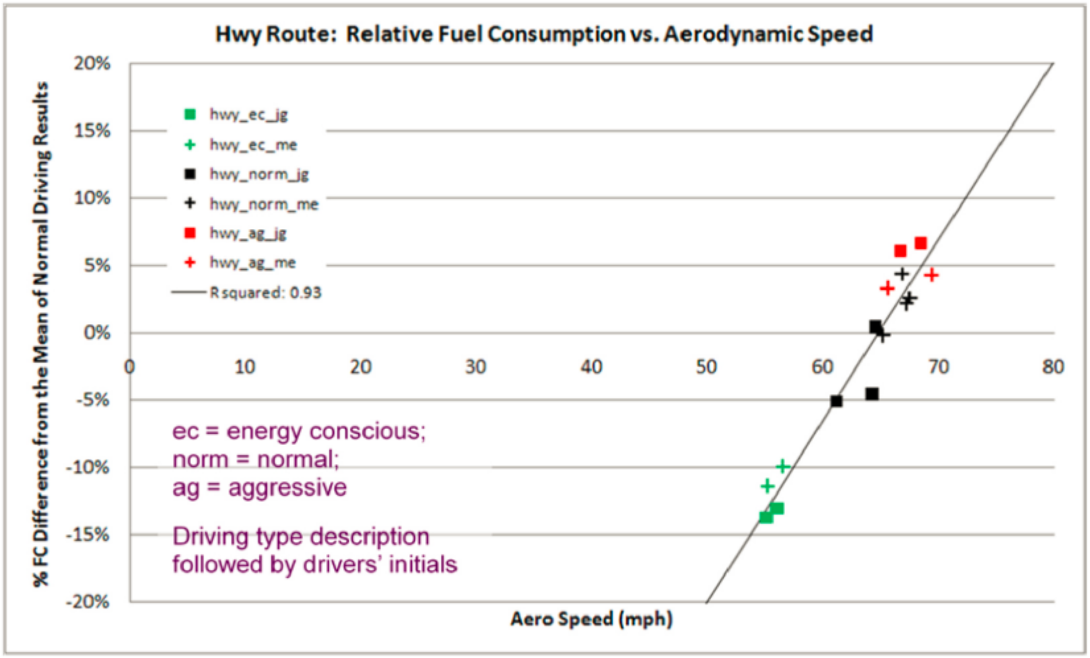


Figure 1-2: Fuel Use Comparison For "Highway" Driving Experiments.

Source: Gonder, J., Earleywine, M. and Sparks, W., "Analyzing Vehicle Fuel Saving Opportunities through Intelligent Driver Feedback," *SAE Int. J. Passeng. Cars - Electron. Electr. Syst.* 5(2):2012, doi:10.4271/2012-01-0494.

A summary of driving behaviors that affect fuel economy include; speed during highway driving, as shown above, frequency of acceleration and deceleration, number of stops, and the timing of gear changes, which, for the driver impact, is only relevant for a manual transmission. After reviewing many of these driving behaviors, and other factors that impact how efficiently a driver performs, various driver feedback systems were proposed. In conclusion to the NREL study it was determined that increasing automation and giving some form of feedback, whether dash lights, sounds, or vehicle responses, could help improve the efficiency of the driver.

A similar study, in a thesis by Irene Berry, on the effects of driving style and vehicle performance on real world fuel consumption of U.S. light-duty vehicles looked to quantify the impact of the driver by developing three aggressiveness factors. Each of these was based on vehicle characteristics but did not acquire data for driver input such as accelerator pedal position. These aggressiveness factors showed good correlation to fuel consumption and are outlined in better detail in section 1.3. In the introduction, of Berry's thesis, she references many other studies that have considered the impact of the driver. They looked at the impact of the drivers in certification testing, similar to fuel economy testing, where the difference in driving can cause up to a 3 percent difference in fuel economy. Berry also investigates eco-driving which is detailed further in section 1.3. Eco-driving is described as a set of skills that the driver must adopt to improve fuel economy. Some of the techniques of eco-driving include avoiding high engine speeds, maintaining steady vehicle speeds, better anticipating traffic conditions, reducing the rate of acceleration and deceleration, and avoiding long idle times. By adopting eco-driving many studies have shown that a driver can reduce fuel consumption by as much as 5 to 10 percent. (Berry 2010)

A final study, by J. A. Joyner of Cummins Engine Co. Inc., dates all the way back to 1965 and gave an overview of the different factors affecting fuel economy in diesel powered vehicles and the importance of fuel economy to long haul fleets. The driver was one of these factors. In the first sentence of the driver section Joyner states, "The driver has more influence over fuel economy than any other single factor. Fleet management should make sure all drivers understand the engine and how to drive for fuel economy."

Of all of the factors mentioned in this study the driver is one that can influence all of the others. For example, the driver determines which gear the transmission is in relative to engine speed and load, whether or not he runs the air conditioning or other accessories, and if the vehicle is maintained with proper tire inflation, engine oil, or engine filters. Responsibility falls on the driver to determine the optimal settings and conditions necessary for improved fuel economy. Even though dated, this study shows that the impact of the driver is not a new thing. (Joyner 1965)

These studies listed are a very small portion of the research done on driver impact on fuel economy. All of the studies referenced in this paper went into detail describing and researching the impact of the driver and driving style on fuel economy. Each have varying results from different applications and different data sets but all of them help drive the main point that the driver most definitely has an impact on fuel economy of any vehicle in any driving condition.

1.2 Importance of Improved Fuel Economy

One of the most obvious reasons for improved fuel economy is the cost of fuel. The cost of both diesel fuel and gasoline continues to increase. Figure 1-3 shows the increase in cost of diesel fuel in the United States over roughly a twelve year period.

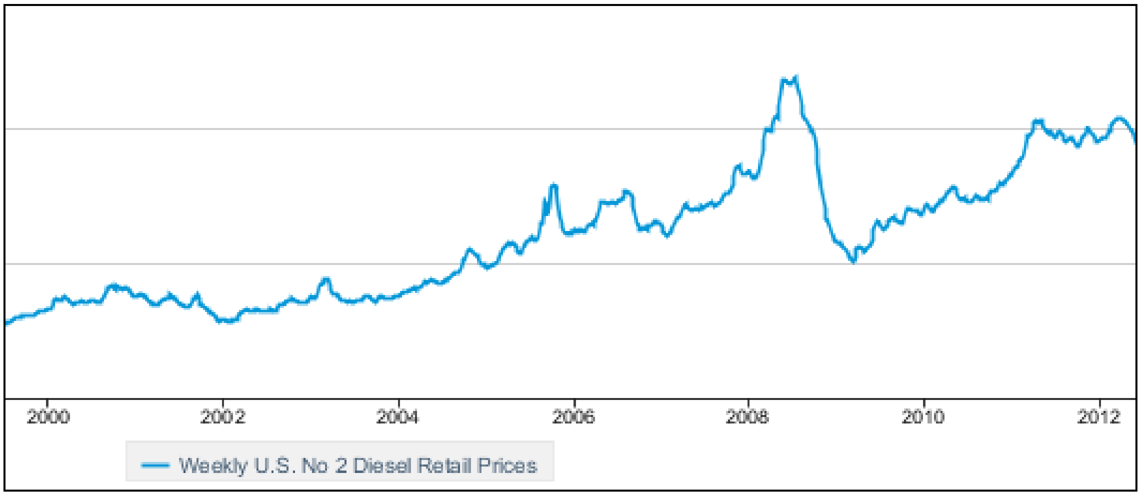


Figure 1-3: Weekly U.S. No 2 Diesel Retail Prices

Source: http://www.eia.gov (September 2012)

Trucking fleets that improve fuel economy by at least 5 percent can save more than $3,000 per truck each year in fuel costs and eliminate 8 metric tons of carbon dioxide emissions per truck each year which leads to the next important impact of reduced fuel consumption. (SmartWay Transport Partnership 2010)

Heavy duty vehicles are one of the leading contributors to emissions in the transportation industry. Nitrous oxides (NOx) and particulate matter (PM) both contribute to serious health problems in the United States and are both a byproduct of the diesel combustion process as well as CO_2 a green house gas. According to a study, by the United States Environmental Protection Agency (EPA), road transport is responsible for about 30% of the total emissions of CO_2 into the air. (U.S. Environmental Protection Agency. 2011) Because of the direct correlation between CO_2 and fuel consumption CO_2 is often times used to measure fuel consumption by the use of portable emissions modules (PEMs). This correlation only helps support the importance of reducing fuel use as it is directly impacting the amount of CO_2 being produced. In recent decades, the EPA has begun limiting the amount of emissions aloud by heavy duty truck and engine manufacturers. Due to stricter regulations many new technologies have been developed to reduce the amount of harmful exhaust emitted by heavy duty trucks. Truck and engine manufacturers as well as the EPA all understand that one way to reduce emissions is to reduce the amount of fuel burned. This is why the EPA has also required that all vehicles on the road today must improve fuel economy and has set requirement for 18% improvement by the year 2018 from year 2010.

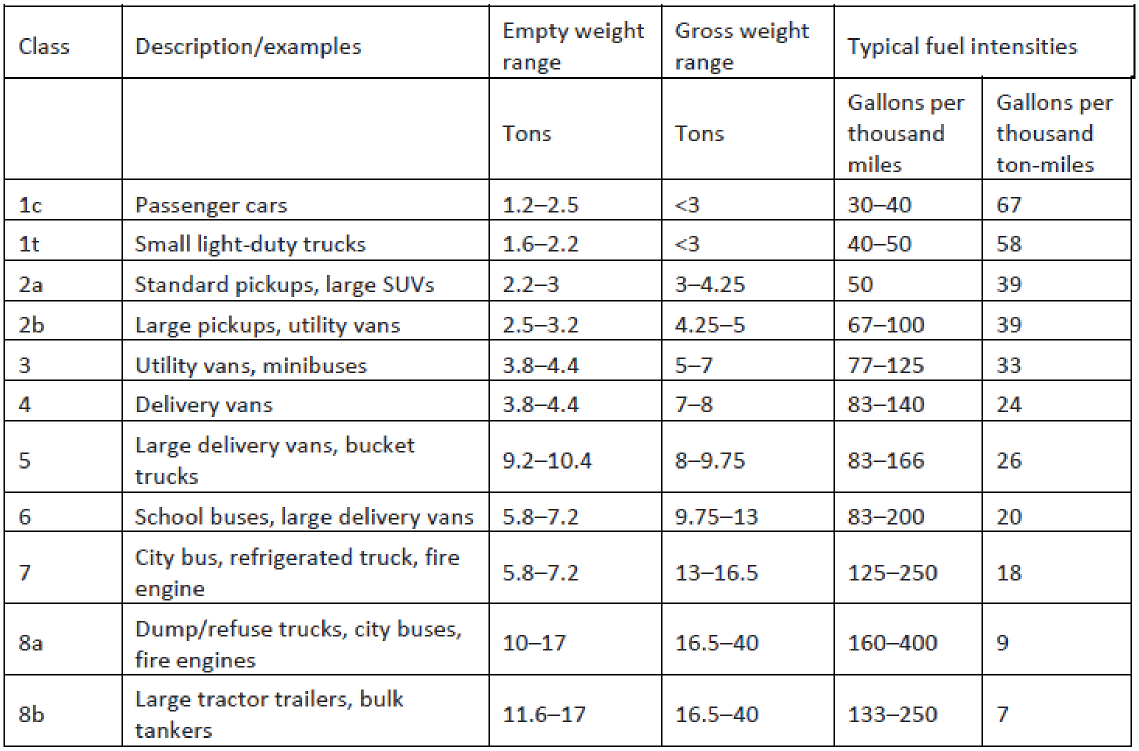
In summary, the importance of improved fuel economy is great. By reducing the amount of fuel today’s vehicles burn cost of fuel and emissions are both reduced. This reduction of emissions is not only a requirement of the government but also an obvious step in the right direction for improving the environment and the health of the public. Along with the reduced emissions is the reduction in cost of operation. By reducing fuel consumption many large fleets can save significantly on fuel costs. For further reading on regulations see “EPA and NHSTA Adopt First-Ever Program to Reduce Greenhouse Gas Emissions and Improve Fuel Efficency of Medium- and Heavy-Duty Vehicles” and “Petroleum & Other Liquids Data”. (U.S. Energy Information Administration 2012)

1.2.1 Fuel Economy Metrics

One of the more popular metrics for measuring fuel economy is miles traveled per one gallon of fuel or mpg. This metric has become the standard benchmark for the automotive industry. While mpg is an adequate measure of fuel economy it can also be misleading. Where an average passenger car might get 20 to 30 mpg, a heavy duty tractor trailer combination will see 5 to 7 mpg. People may understand that this difference is due to weight but many of them probably don’t realize that the tractor trailer is actually outperforming the passenger car when it comes to the amount of work done.

When taking the weight of a vehicle into consideration a different metric is available called Ton-mpg. A typical passenger car weighs around 1.5 to 2 tons while a tractor trailer combination can weigh as much as 40 tons with a full load. By including the weight of the vehicle along with mpg a gauge for productivity or work is created. For example, taking the weight of the car multiplied by its mpg yields 30- 60 ton-mpg and of the tractor trailer combination yields around 200 ton-mpg. From this it can be seen that the productivity of the tractor trailer combination is much greater. Because of the higher magnitude of the truck weight with a load an improvement in fuel economy is more significant. If the fuel economy of a heavy duty tractor improves by 1 mpg it will increase productivity 30 to 40 ton-mpg while a passenger car will only increase its productivity by 2 ton-mpg. Table 1-1 shows the differences between fuel used and work done between different classes of vehicles over a distance of 1000 miles which helps support the relevance of using ton-mpg for heavy duty trucks. (Harrington W. 2012)

Table 1-1:Vehicle Weight Classes Defined by U.S. Department of Transportation



Class	Description/examples	Empty weight range	Gross weight range	Typical fuel intensities	
		Tons	Tons	Gallons per thousand miles	Gallons per thousand ton-miles
1c	Passenger cars	1.2–2.5	<3	30–40	67
1t	Small light-duty trucks	1.6–2.2	<3	40–50	58
2a	Standard pickups, large SUVs	2.2–3	3–4.25	50	39
2b	Large pickups, utility vans	2.5–3.2	4.25–5	67–100	39
3	Utility vans, minibuses	3.8–4.4	5–7	77–125	33
4	Delivery vans	3.8–4.4	7–8	83–140	24
5	Large delivery vans, bucket trucks	9.2–10.4	8–9.75	83–166	26
6	School buses, large delivery vans	5.8–7.2	9.75–13	83–200	20
7	City bus, refrigerated truck, fire engine	5.8–7.2	13–16.5	125–250	18
8a	Dump/refuse trucks, city buses, fire engines	10–17	16.5–40	160–400	9
8b	Large tractor trailers, bulk tankers	11.6–17	16.5–40	133–250	7

Source: Harrington W. and Krupnick A., "Improving Fuel Economy in Heavy Duty Vehicles", Resources for the Future Issue Brief 12-01 March 2012

For this research the fuel economy metric miles per gallon is used. Due to the fact that the loads of the two trucks are being kept the same the Ton-mpg metric is not necessary. With trucks running the same distance the fuel consumption metric could have also been used but mpg was chosen due to familiarity and general understanding by most individuals.

1.2.2 Fuel Economy Testing

Fuel economy test procedures are developed to best show comparative fuel consumption results. The Society of Automotive Engineers (SAE) has defined set test procedures for running fuel economy testing of on highway vehicles. As of current there are three different types of SAE Fuel Economy test procedures for measuring the fuel consumption of heavy duty trucks and buses. Each of these procedures requires a great deal of planning and organization. The main concern in fuel economy testing is to eliminate all variability due to differences in fuel, weather, drivers, route changes, traffic, and the like. The more controlled the test the better. Following is a brief overview of the three SAE fuel consumption tests.

SAE J1264 Type I Fuel Consumption Test Procedure is best suited for testing components or systems that can be easily switched between two vehicles. This may include aero devices, clutch fans, tires, and more. This test is used to determine the fuel economy benefit of the device in question.

SAE J1321 Type II Fuel Consumption Test Procedure is designed for test track or on road testing of two identical vehicles. One vehicle is the control vehicle and the other is the test vehicle. The control vehicle stays the same throughout the testing while changes can be made to the test vehicle to see what their impact is. This type of test is useful for testing components that take longer to change such as the engine, transmission, axle, or the like.

SAE J1526 Type III Fuel Consumption Test Procedure is best suited for two vehicles that are not identical but where quantifying the differences in fuel economy is desired. This test is specifically designed to be completed in one day on a test track.

For this study the type II test procedure was followed as closely as possible and is described in more detail in Chapter 2:. It is important to note that other organizations have developed similar fuel economy test procedures including but not limited to The Technology &Maintenance Council (TMC), National Highway Traffic Safety Administration (NHSTA), and SmartWay a partnership with the EPA. This list is given for anyone interested in running fuel economy testing.

1.3 Defining Aggressivity

As stated in the beginning of this chapter, many studies have been done on the impact of the driver on fuel economy and emissions. Some of these studies made an attempt at developing a metric to be used to correlate the impact of the driver on fuel consumption. After extensive research four different driver variability or aggressivity metrics were discovered for possible use in this paper. Each metric and its corresponding study are outlined in this section. All of the methods described were involved in either fuel consumption or emissions reduction studies. The first two studies were found to require more extensive testing while the later two were viewed to be more suitable for the test performed for this paper of which the final one was chosen.

The first study, by Irene Berry, took an extensive look at the effects of driving style and vehicle performance on fuel consumption. This study developed an aggressivity factor that incorporates coast down ABC coefficients and therefore requires coast down testing which is described in SAE J1263. The ABC coefficients are used to compensate for the multiple on road resistances that a vehicle sees while in operation. These include tire rolling resistance, drag from brake pads and wheel bearings, power used by pumps of the vehicle, and aerodynamic drag. Equation 1-1 shows the equation used for city driving.

$$AF_{city} = \left(\frac{1}{M}\right)\left[\left(\frac{\int (Av + Bv^2 + Cv^3 + Mav)^{+} dt}{\int vdt}\right) - \left(Roadload(\bar{v})\right)\right] \qquad (1\text{-}1)$$

$$Roadload(\bar{v}) \propto \frac{\int (Av + Bv^2 + Cv^3)dt}{\int vdt} \qquad (1\text{-}2)$$

Where A, B, and C are the coefficients derived from a coast down test, v is the vehicle velocity, and M is the vehicles mass. Equation 1-2 shows the Road load equation which is comprised of the same variables as listed above. Figure 1-4 shows the strong correlation between fuel consumption and the city aggressiveness factor of a Ford Focus passenger car. For every 1 m/s^2 increase in city aggressiveness causes an increase of 4.4 L/100km in fuel. A total of three aggressivity factors were developed in this study, one for city driving, one for highway and one for neighborhood. Each of the three metrics has the same general equation with minor changes to take into account the varying impact of particular parameters. For example, vehicle speed has a greater impact on fuel economy for a highway run than what acceleration does. For city driving it is the opposite and for neighborhood driving acceleration has an even greater impact that vehicle speed. (Berry 2010)

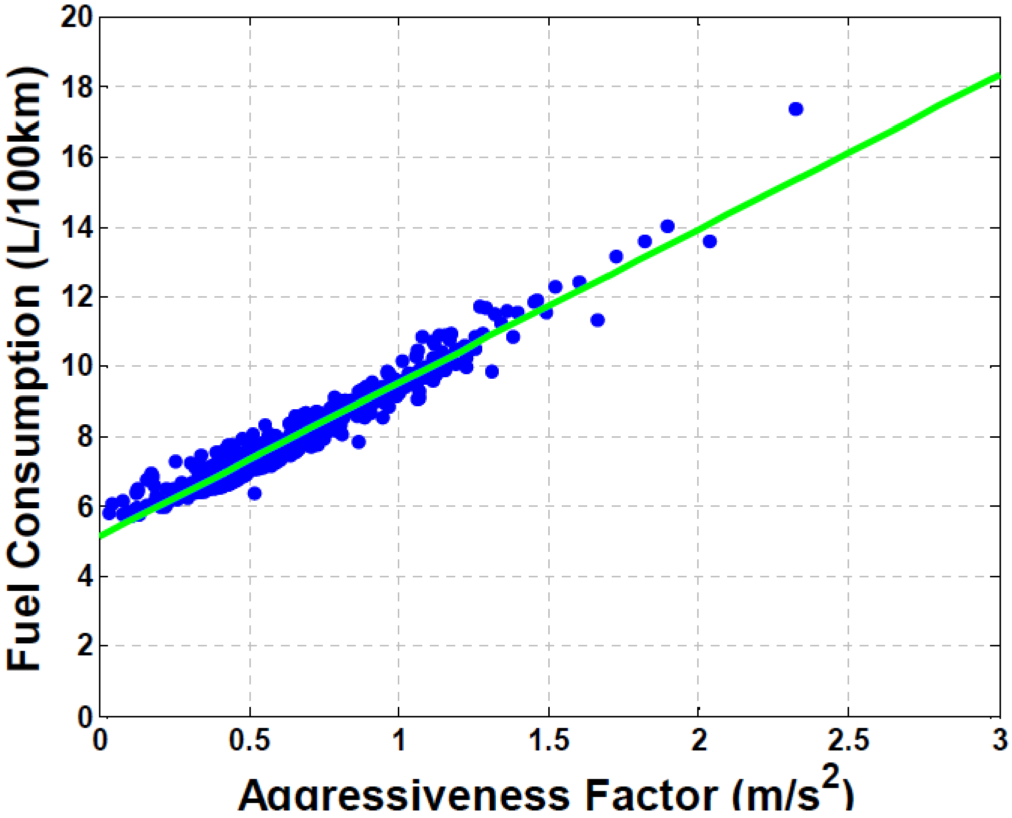


Figure 1-4: Fuel Consumption versus city aggressiveness factor.

Source: Berry, Irene Michelle. *The Effects of Driving Style and Vehicle Performance on the Real-World Fuel Consumption of U.S. Light-Duty Vehicles.* Masters Thesis, Massachusetts Institute of Technology, 2010.

Although this metric shows strong correlation it could not be used due to the lack of a proper coast down test location as well as the availability of a sufficient on vehicle anemometer setup. Coast down testing was performed but only to ensure that the two vehicles being tested had no significant differences in drag. Out of the four metrics overviewed in this section the aggressiveness factor developed by Berry shows the strongest correlation against fuel consumption. If all conditions for a proper coast down test can be met, this metric would be highly recommended.

The second study considered was actually referenced in the first and focused on how driving style can influence car CO_2 emissions. The authors of this study understood the need to develop a methodology to assess and quantify the influence of the driver on the vehicle's fuel consumption. The metric in this study is defined as eco-index and takes a different approach on driver impact. The goal of eco-index is to take data from an existing drive cycle, modify it, and then through simulation of the drive cycle see if the driver had adopted the eco-driving style what would be the results on fuel consumption and CO_2 emissions. An example of a modified drive cycle overlaid onto the original is shown in Figure 1-5. Unfortunately the authors of this work did not disclose an in depth description of how the algorithm worked and specified that further detail would be revealed in future work. (Alessandrini 2011)

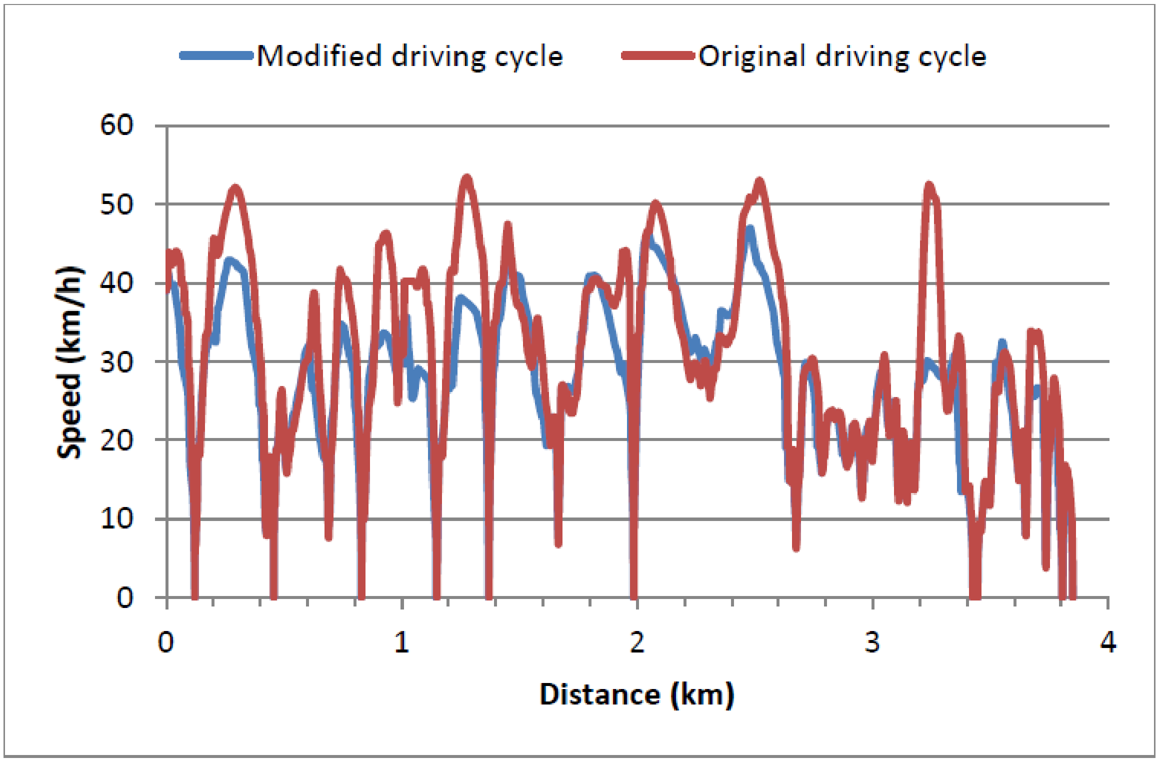


Figure 1-5: Comparison between a modified cycle and the corresponding original one as a function of the traveled distance.

Source: Alessandrini, A., Cattivera, A. Filippi, F. Ortenzi, F. *Driving Style Influence on Car CO2 Emissions.* Sapienza Unuversity Rome: CTL Centre for Transport and Logistics, 2011.

The third study by the Ford Scientific Research Laboratory looked at emissions from varying levels of driver aggressiveness and in doing so developed a metric to measure driver behavior that they called, “aggressivity” as seen in equation 1-3 and 1-4.

$$P_f = 2 * v * a \tag{1-3}$$

$$Vehicle\ Aggressivity \equiv RMS(P_f) \equiv \sqrt{\frac{1}{N}\sum_{i}^{N} {P_{fi}}^2} \tag{1-4}$$

The Root Mean Square (RMS) is taken of the power factor (P_f) which is comprised of v, vehicle speed or velocity in mph, and a, vehicle acceleration in mph/s. N is the number of events that occur in a drive cycle. In this study it was found that aggressive driving produced significantly more CO and HC emissions as can be seen by comparing the measured values in Figure 1-6.

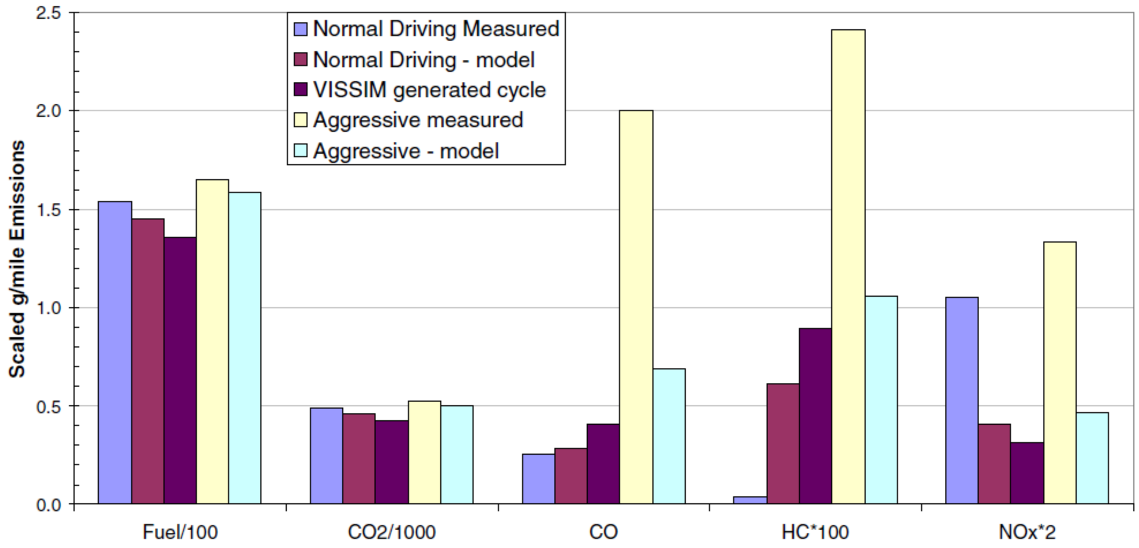


Figure 1-6: A comparison of measured and modeled fuel consumption and emissions for different driver behaviors.

Source: Nam, Edward K., Gierczak, Christine A, Butler, James W. "A Comparison Of Real-World and Modeled Emissions Under Conditions of Variable Driver Aggressivness." *TRB 2003 Annual Meeting* (Ford Scientific Research Laboratory), 2002.

Figure 1-7 shows modeled emissions results with the RMS(P_f). A good correlation of increasing emissions relative to increasing aggressivity can be seen. The aggressivity metric in this study by itself does not show as significant of a correlation to fuel economy as would be preferred which can also be seen in Figure 1-6. (Nam 2002)

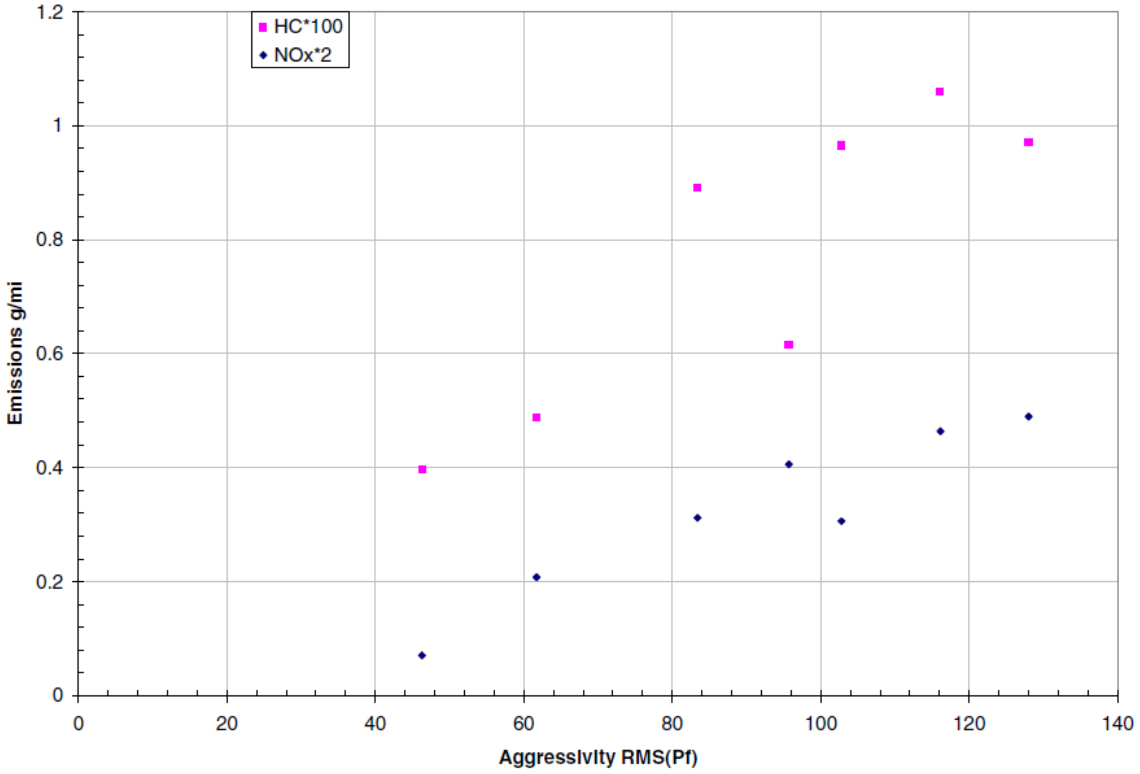


Figure 1-7: Modeled HC and NOx emissions as a function of driver aggressivity. CO trends (not shown) are similar.

Source: Nam, Edward K., Gierczak, Christine A, Butler, James W. "A Comparison Of Real-World and Modeled Emissions Under Conditions of Variable Driver Aggressivness." *TRB 2003 Annual Meeting* (Ford Scientific Research Laboratory), 2002.

The final study, conducted by MAHLE Powertrain Ltd., took the aggressivity described above and added a proposed pedal aggressivity metric similar to the RMS(P_f) method. This metric takes into consideration the inputs by the driver and combined with the previously described vehicle aggressivity in equation 1-4 we now have a total aggressivity equation 1-5. Aggressivity in equation 1-5 has been abbreviated to Aggr.

$$Total\ Aggr. = \sqrt{Vehicle\ Aggr.} + \sqrt[4]{Pedal\ Aggr.} \tag{1-5}$$

This study goes into more detail of how to apply the aggressivity metrics. It is made clear that the vehicle speed and acceleration used are the averages for an acceleration profile. An acceleration profile goes from adjacent minimum and maximum vehicle speed points. Only positive accelerations were used by this study.

The pedal aggressivity shown in equation 1-6 takes the root mean square of the pedal power factor.

$$Pedal\ Aggressivity, (\frac{\%^2}{s}) = \sqrt{\frac{1}{N}\sum_{i}^{N} {P_{f(Pedal)}}^2} \tag{1-6}$$

$$Powerfactor_{(Pedal)} = 2 * Pedal * (\frac{Pedal}{s}) \tag{1-7}$$

The pedal power factor is comprised of pedal which is the average percent throttle position for an acceleration profile and then using the defined sample rate the average pedal rate for the profile is derived as well. All vehicle parameters for this metric are acquired from the vehicle data link. The goal of the Total aggressivity metric is to eliminate any differences between vehicles to only focus on the impact of the driver. For example if a passive driver were to drive a very aggressive vehicle it would not yield an accurate comparison against an aggressive driver driving a passive vehicle. The total aggressivity metric helps normalize between vehicles. An example of the total aggressivity output can be seen in Figure 1-8. (Daniel 2009)

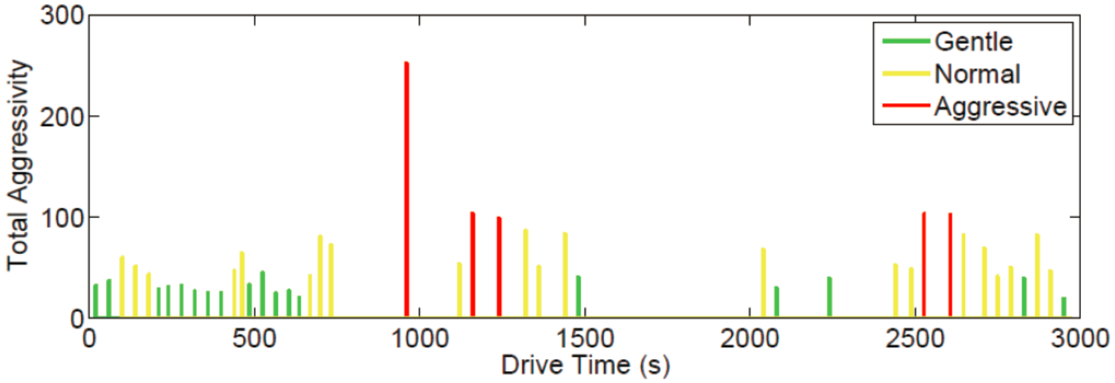


Figure 1-8: Example output of the total aggressivity stem plot time trend analysis.

Source: Daniel, R., Brooks, T., and Pates, D. "Analysis of US and EU Drive Styles to Improve Understanding of Market Usage and the Effects on OBD Monitor IUMPR." *SAE Technical Paper 2009-01-0236*, 2009: doi:10.4271/2009-01-0236.

1.4 Objectives

The goal of this study is to investigate driver and vehicle aggressivity, using different metrics, during a modified type II on road SAE fuel consumption test. The vehicles being tested are two identical tractor trailers powered by a heavy duty engine paired with a 10 speed manual transmission. Two drivers with real world tractor trailer experience, but no fuel economy driving experience, were hired. From this study there are many questions to be answered. Three of the main questions are listed below.

1. Does the SAE type II fuel consumption test procedure requirement of maintaining the same driver for the entire test prove to be the best option for on road testing?
2. How accurately do the aggressivity metric described in this paper distinguish between two drivers when they are asked to drive as close to the same as possible?
3. What is the best metric for relating driver and/or vehicle aggressivity to fuel economy during a controlled test where the goal is to have as little discrepancy between drivers as possible?

CHAPTER 2: TEST PROCEDURE

2.1 SAE Type II Fuel Consumption Procedure

The SAE J1321 Type II Fuel Consumption Test Procedure was followed as closely as possible for this research. The test was not exclusively run for the purpose of this study on driver impact and therefore has differences that would not be recommended but the data acquired is still deemed adequate and relevant. The following is a summary of the details and limitations pertaining to the test performed.

2.1.1 Vehicle Type, Configuration and Weight

The SAE type II Fuel Consumption Test requires that the two vehicles being tested be of the same make and model. There should be no differences in tires, engines, transmissions, aerodynamics, and any other hardware that can impact fuel economy. Along with the tractors it is important that the trailers be the same. Tractor trailer weight must also match between the two trucks. This should be checked with the trailers swapped between tractors to verify. For the initial base line test it is of utmost importance that the two vehicles be as close to identical as possible. For this test the two vehicles being tested were identical Freightliners with matching bodies, engines, transmissions, axles, and tires. The trailers were also like Rider trailers with matching tires. Some of the more detailed information on the trucks cannot be disclosed due to confidentiality. The weight of the two trucks was 66,315 lbs and was checked before and after the test.

2.1.2 Test Route and Speeds

The test route chosen was a rural route consisting of approximately 80% stop and go driving at transient speeds and 20% highway driving. Due to this being an on road test the route is required by SAE type II test to be greater than 100 miles. The route chosen had a distance of 122 miles and was driven for two laps for a total of 244 miles. The start and the stop of the route was the same location.

2.1.3 Drivers

The SAE type II test procedure requires that the drivers stay with the same truck for the entirety of the test but for this test the drivers were swapped. After the first leg of the test the drivers were asked to switch trucks and then again after the third leg. It was considered relevant to have the drivers switch to eliminate any variability due to different driver behavior. The drivers chosen were also experienced drivers hired from a truck driver company.

2.1.4 Weather Considerations

The weather conditions were recorded at the beginning, middle, and end of each lap of the test. The data was collected using a handheld kestrel 4500 weather meter and included wind speed, wind direction, and temperature. Per SAE requirements, no test was included if the average wind speed for the run was greater than 12mph or if the temperature gradient were greater than 30 °F. It can be seen from Table 2-1 that the temperature difference for all of the runs fell within the 30 °F limit. Also, the temperature of the fuel was measured. Diesel fuel has a coefficient of expansion of 0.0005/°F. For every 1 degree change in temperature the fuel correction is 0.05%. For the highest average difference in fuel temperature of 3.22 °F, as seen in Table 2-1, the fuel volume difference would have been 0.161% or roughly 0.00161 gallons of fuel for every gallon used. Most all of the runs would require a fuel correction of roughly 0.1% and therefore were not changed due to this being a consistent value throughout the test. The shift of the data will not impact the correlations seen.

Table 2-1: Weather averages and deltas for each day.

Run Averages & Delta			
	Temp Change (°F)	Wind Speed (mph)	Fuel Temp Delta (°F)
12-Jul	10.9	4.68	1.6
13-Jul	19.9	2.54	1.16
16-Jul	12.1	2.48	0.56
17-Jul	20.4	2.6	1.4
18-Jul	11.2	3.1	1.64
19-Jul	12.4	2.1	1.94
20-Jul	10.1	2.78	3.22

2.2 Instrumentation and Equipment

This section outlines the instrumentation used which included a fuel flow meter, weather meter, and a data logger.

2.2.1 Fuel Flow Meters

Measuring the fuel used during the test is the most important aspect. SAE recommends the use of gravity weigh tanks but also allows for the use of portable emissions modules (PEMs) or volumetric flow meters. For this test a volumetric flow meter was used calibrated to an accuracy of 1%.

Measuring the fuel flow of a diesel engine has an added obstacle that measuring gasoline engines does not. Many of the diesel engines used in heavy duty tractor trailer applications utilize a high pressure fuel injection system that requires a pressure relief valve. This relief valve allows unburned fuel to return to the fuel tanks. This return fuel thus prevents a flow meter from being able to be installed only on the feed line to the engine. Also this return fuel is of an elevated temperature. To overcome these road blocks a flow meter specifically design for this type of application was used.

The flow meters have an intuitive design that utilizes check valves, a pump, cooler, thermocouple, and a filter. Fuel is drawn from the tanks and passed through a filter installed on the flow meter. This fuel then passes through a continuous flow pump that pumps the fuel to a T-intersection. At the T-intersection the fuel will be passed through a cooler or is drawn through the volumetric flow meter by the engine. The fuel that passed through the cooler is used to cool the return fuel from the engine and is then returned to the tanks. The cooler fuel and engine return fuel do not mix. After the engine return fuel has been cooled it is then fed back to the engine supply but after the flow meter as to not be counted a second time. This process allows for the return fuel to be cooled as needed without effecting the fuel measurement. A basic diagram of how the fuel flow meter works is shown below in Figure 2-1.

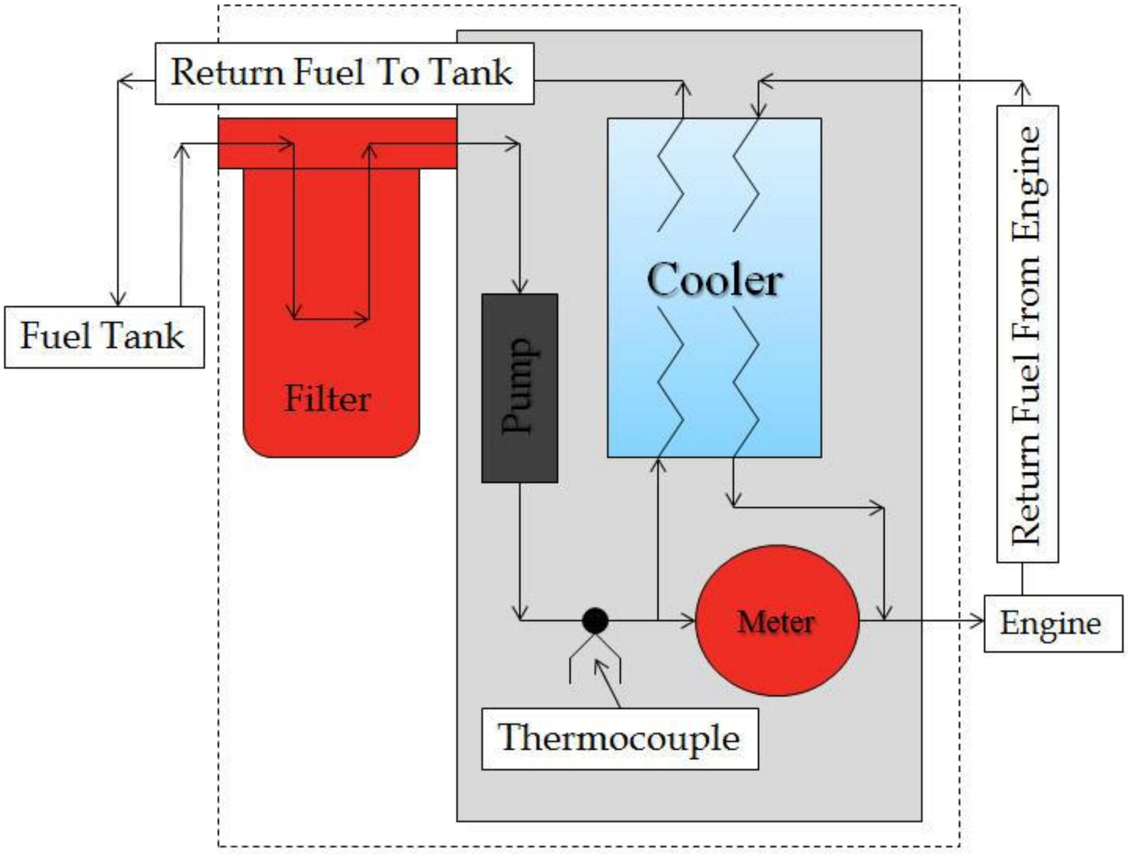


Figure 2-1: Fuel Flow Meter Operational Diagram.

The actual meter utilizes rotary piston technology. Each revolution of the piston produces a pulse output which is called a count and one count is equal to a given quantity of fuel. Figure 2-2 shows the step by step operation of this design. With the system being based on volume and not weight, as in the weigh tank method, adjustment for density is not necessary unless a difference in fuel temperature exists. This is why the thermocouple as seen in Figure 2-1 is available. Temperature measurements are taken before, during and at the end of the test to ensure that the fuel between the two trucks maintains the same temperature difference through the entire test.

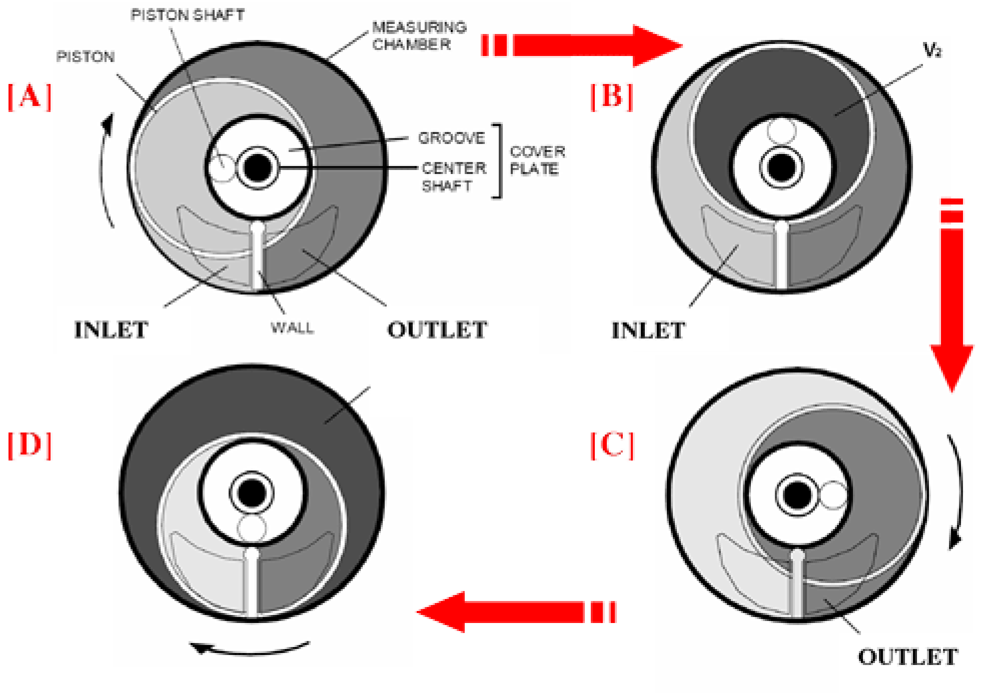


Figure 2-2 Rotary Piston Operation

Source: http://www.flowmeters.info/wiki/images/a/a6/Technorotary.gif

2.2.2 Weather Meter

A handheld Kestrel 4000 weather meter was used to collect weather data at the beginning, middle and end of each test run. The SAE test procedure requires that weather data be taken, at the least, at three locations along the route. The Kestrel weather meter is capable of taking temperature, wind speed, wind direction, and atmospheric pressure.

2.2.3 Data Loggers

Data loggers with special software were used on both trucks to collect data from the J1939 CAN network. All truck manufacturers are required to broadcast certain pre defined parameters on the J1939 public network. The logger used for this testing is capable of gathering any data broadcast on the public network as well as GPS data gathered from the built in GPS processor and included antenna. Once the data has been acquired it can be downloaded either directly from the logger or can be sent directly from the logger through a cellular antenna to a server where it can be retrieved at a later time.

2.3 Data Acquisition

Data was collected from the J1939 CAN public data link. For this test six parameters were logged by the data logger which included time, vehicle speed, engine speed, net engine torque, accelerator pedal position, and fuel flow meter counts. The log rate was 1Hz or a data point ever second. The data is automatically stored in a CSV file format by the logger software which can be extracted at a later time by an engineer or technician. Once all data is collected the data is processed using Matlab and excel.

CHAPTER 3: METHODOLOGY

3.1 Modified Driver Aggressivity Method Used

The total aggressivity method developed by MAHLE Powertrain Ltd mentioned in section 1.3 was modified slightly to be used for this test. Instead of looking at an acceleration profile that goes from adjacent minimum and maximum vehicle speed points each individual time interval was considered. Only positive accelerations were used by their study which was maintained. This method looks at the average speed and acceleration over an acceleration event and then normalizes by the number of events. This same technique is used for the pedal aggressivity as well. It was concluded from analyzing various data sets and understanding how driving behavior impacts fuel economy that processing the data in a more micro instead of macro method could actually improve correlation to fuel consumption. Where the original total aggressivity method only looks at acceleration events and ignores steady state driving the modified method takes into consideration the fluctuations that may occur during steady state driving. A good driver tends to maintain a more consistent speed during highway driving while a more aggressive driver can tend to treat the accelerator pedal as more of an “on/off switch”. By applying the total aggressivity metric to each individual time step these variations at steady state may be included in the results and provide correlation to fuel consumption. The resulting correlations of this method are discussed in Chapter 4:.

3.2 Proposed Aggressivity Metric

Average positive and negative vehicle acceleration showed the best correlation to fuel consumption. Vehicle speed also showed a strong correlation to fuel consumption. These correlations can be seen in Figure A-1, Figure A-2, and Figure A-3. These three parameters were combined in an equation to generate a good correlation to fuel consumption. Equation 3-1 shows the equation used for acceleration and vehicle speed correlation to fuel consumption. This metric for this study is called the proposed aggressivity (PA).

$$PA = \frac{Positive\ Acceleration * 2 - Negative\ Acceleration * 1}{(Vehicle\ Speed \neq 0) * 0.8 + 1} \tag{3-1}$$

Each of the coefficients in equation 3-1 was determined to produce the best regression fit to fuel consumption with a R^2 value of 0.72. The line fit can be seen in Figure 3-1.

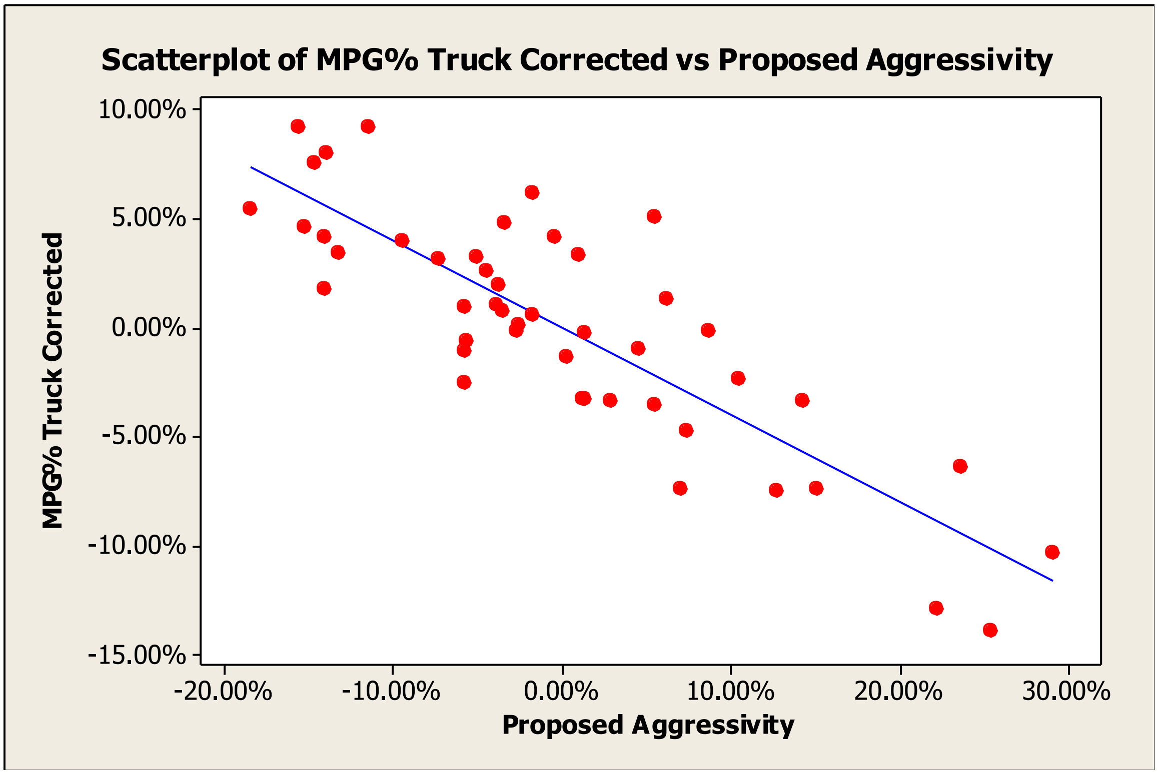


Figure 3-1: Correlation between proposed aggressivity and percent MPG difference from the mean.

CHAPTER 4: DATA ANALYSIS AND RESULTS

After the test concluded and all data had been collected analysis was performed. Matlab, excel, and Minitab were all used to process the data to produce graphs and statistical results. Matlab was used to derive acceleration from vehicle speed and time. Similarly, accelerator pedal rate was derived from accelerator pedal position and time. Acceleration and pedal acceleration were both split up into positive and negative data sets and then the averages were found for each leg of the test. Averages were also calculated for the other parameters listed in Table 4-1. An example of the daily data collected for one truck can be seen in **Error! Reference source not found.** of the appendix.

Table 4-1: Parameters that were collected, calculated, and averaged per leg of the test.

Parameter
Acceleration Negative
Acceleration Positive
Accelerator Pedal Rate Negative
Accelerator Pedal Rate Positive
Accelerator Pedal Position
Vehicle Speed
Average Vehicle Aggressivity
Average Pedal Aggressivity
Average Total Aggressivity
Engine Speed
Engine Torque
MPG
Pedal Position Excluding Zero
Vehicle Speed Excluding Zero

4.1 Analysis of Modified Driver Aggressivity Method

The modified driver aggressivity method was analyzed first to find if any correlation might exist. It was found that the only close correlation from this method came from the vehicle aggressivity portion as shown in Figure 4-1. The pedal aggressivity and the total aggressivity showed no strong correlation to fuel economy. These two comparisons can be seen in Figure A-4 and Figure A-5 of the appendix. The correlation found in the vehicle portion of this metric led to the proposed aggressivity metric discussed in the next section.

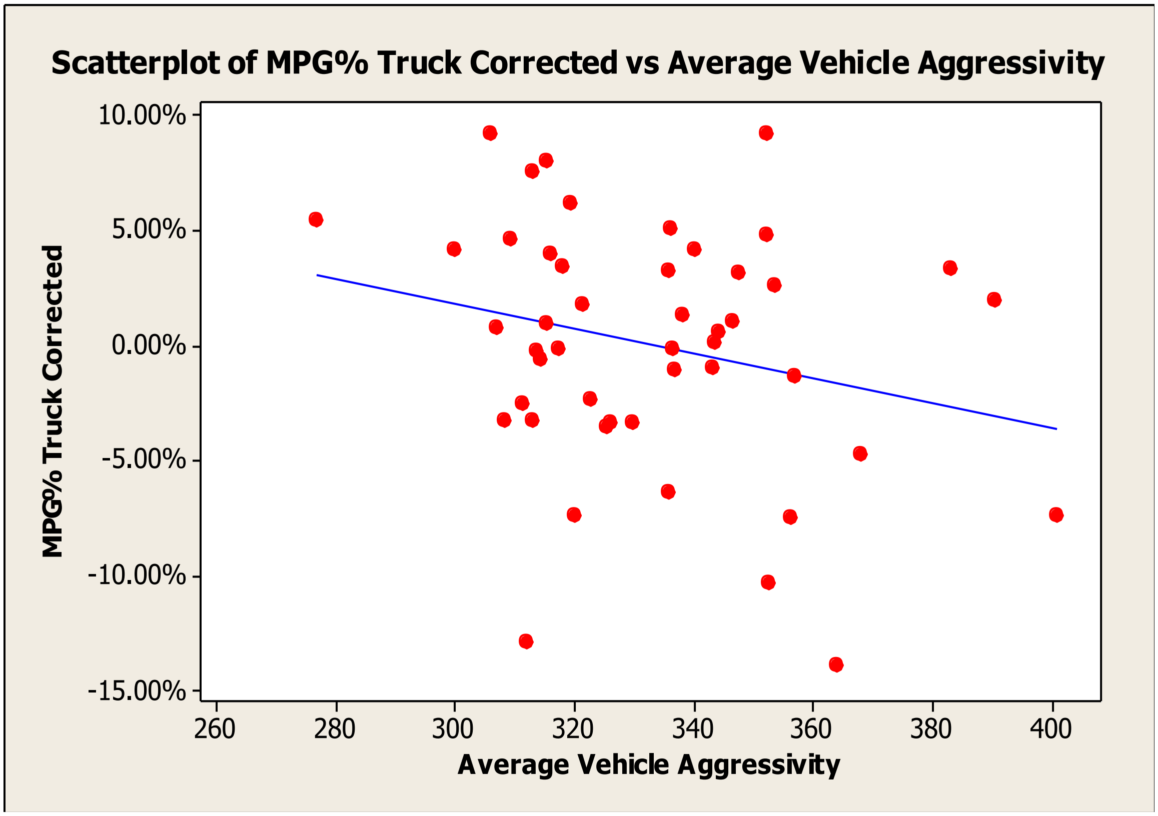


Figure 4-1: Correlation between average vehicle aggressivity and percent difference MPG from the average.

4.2 Analysis of Proposed Aggressivity

The first step was to compare the differences between the two trucks and make a correction. The correction to the trucks was applied and can be seen in Figure A-7 where the difference between the average MPG values went from 1.6% to 0.3%. All of the daily tests were separated and then divided up into four legs based on the outbound and inbound sections of the route. Figure 4-2 shows that each leg has a correlation to different accelerations that follow the same general impact on fuel economy. Unfortunately this impact could not be corrected due to each leg not being identical routes. Leg 1 and leg 3 were the same as well as leg 2 and leg 4 but this still does not help reduce the data. The variability in fuel consumption between each leg is most likely a combination of traffic conditions, engine warm up at the beginning, and possibly a change in temperature that occurs from mid afternoon to night. Due to none of these factors being directly correlated to each other it makes it difficult to correct as correcting one may skew one of the other factors. It can be shown in Figure A-6 that the drivers maintain similar fuel economy and proposed aggressivity correlation for each individual leg.

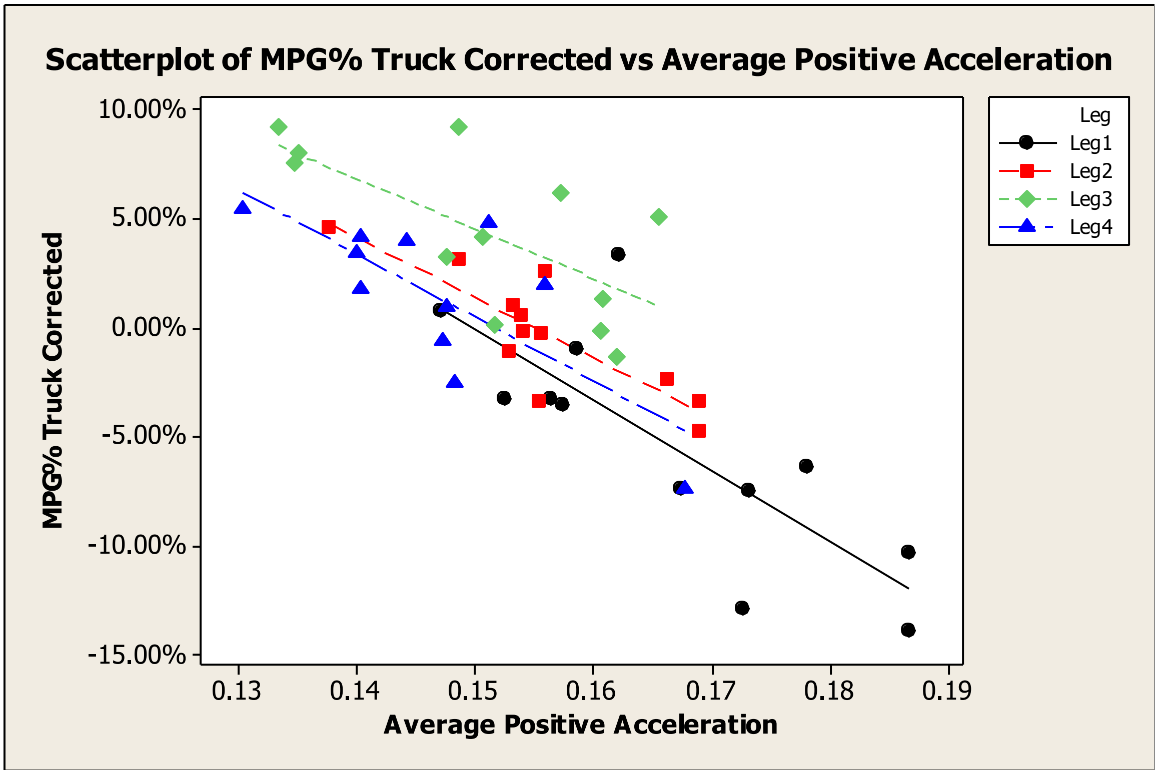


Figure 4-2: Average positive acceleration impact on fuel economy per each leg.

After further investigation it was proposed that the impact of route length should be investigated. It has been shown, in previous tests, by increasing the mileage of the route variability in fuel consumption results decreases. This correlation can be seen in Figure 4-3. The fuel economy results from the drivers driving only a single leg shows a variability of up to 10% while when the full route is ran for one lap, the variability decreases to 7.5% and yet another decrease in variability occurs when the route is ran twice bringing the variability down to roughly 5%.

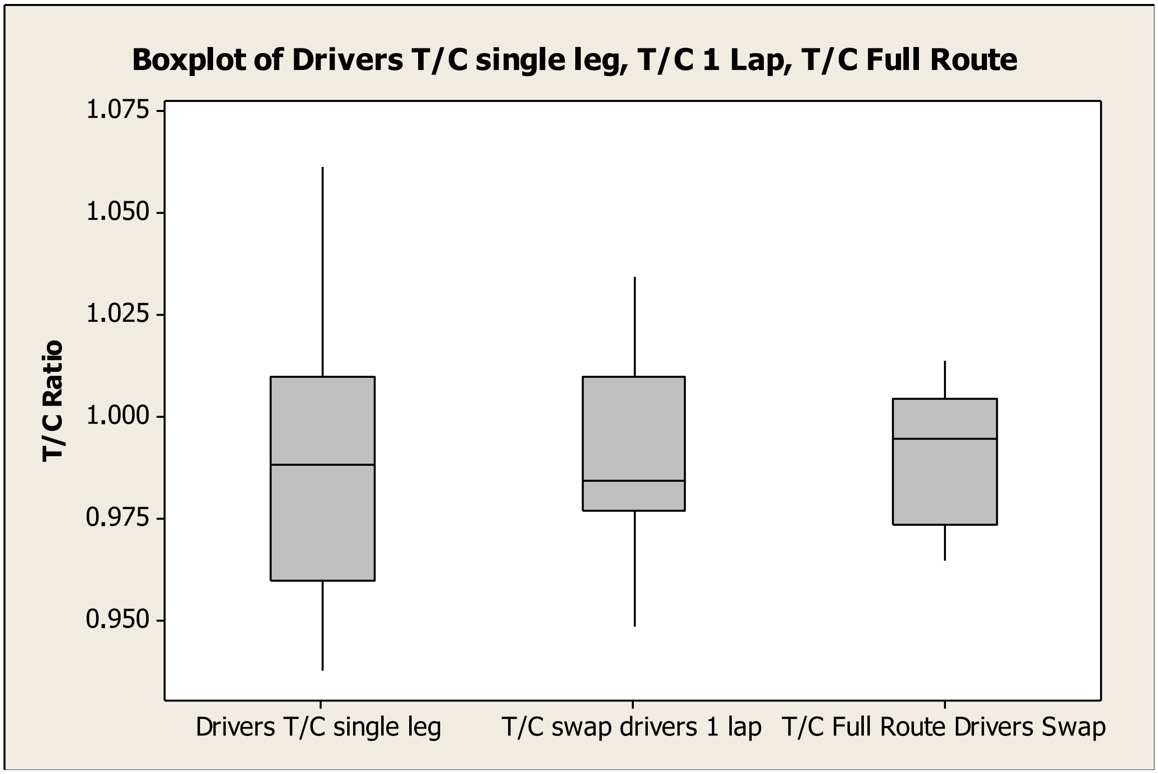


Figure 4-3: T/C comparison for single leg vs. 1 lap vs. full route.

Unfortunately it cannot be concluded from Figure 4-3 whether the drivers switching or extending the length of the route produced the reduced variability. Additional testing would be required to better determine how each factor influenced the results.

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

Based on the results it can be seen that, by asking two drivers to drive as close to the same as possible, the impact on fuel economy testing was less apparent when compared to the extremes seen in the real world. Unfortunately not all of the aggressivity metric described in this paper were able to be used and the modified root mean squared power factor method did not show a good correlation for determining driver impact on fuel economy. The proposed aggressivity metric described in this paper may be applicable for determining driver impact on fuel economy testing but further tests would need to be done to confirm. Although the results of this particular test showed a good correlation and desired results, this might not always be the case. It should be noted that the drivers used for this test were hired from a truck driving company and both were experienced although not in fuel economy testing. It is also recommended that the metric by Irene Berry be tested to determine if it is applicable. Further testing should be conducted with a larger data set that includes varied skill level of the drivers. As well as the driver impact, it could be seen that the time of day also had an influence on fuel consumption. It could not be determined which of the factors related to time of day was causing the shift in fuel consumption but they included, warm up during first leg, traffic changes, and temperature drop. Better controlling these conditions for the driver impact study is recommended for future testing and possible investigation of which of these factors influences fuel economy.

APPENDIX

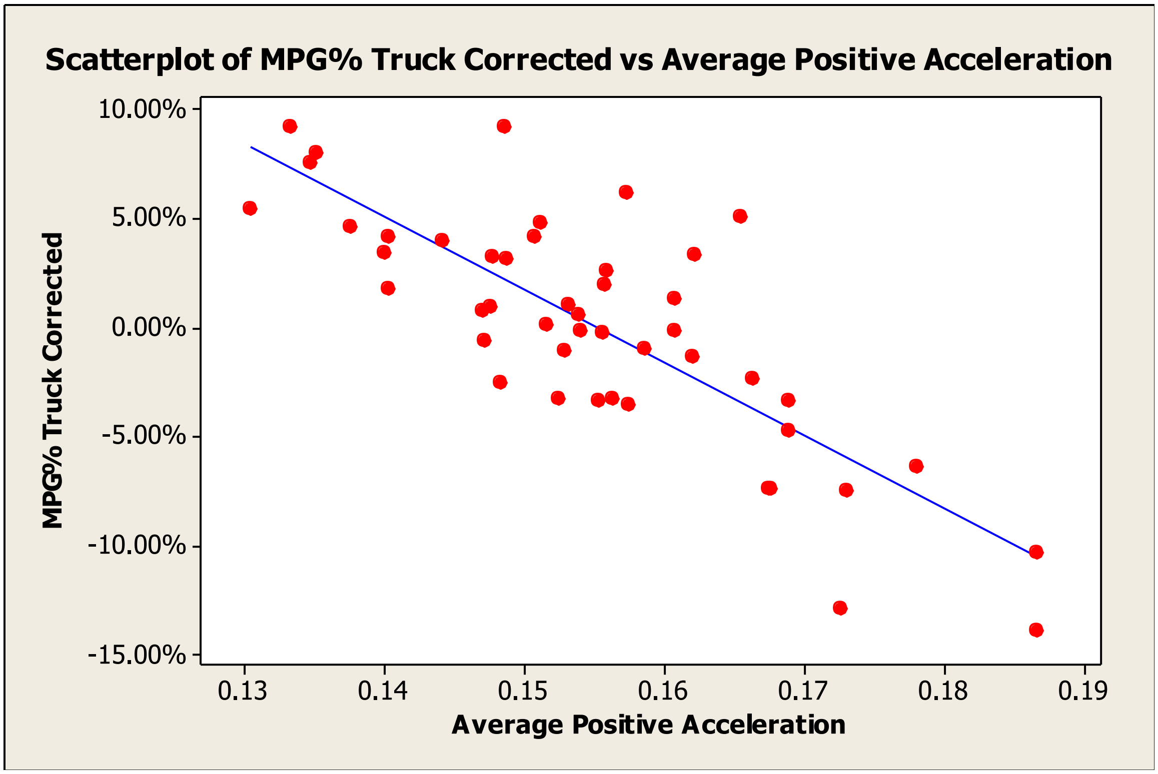


Figure A-1: Correlation between average positive acceleration vs. percent MPG difference from mean.

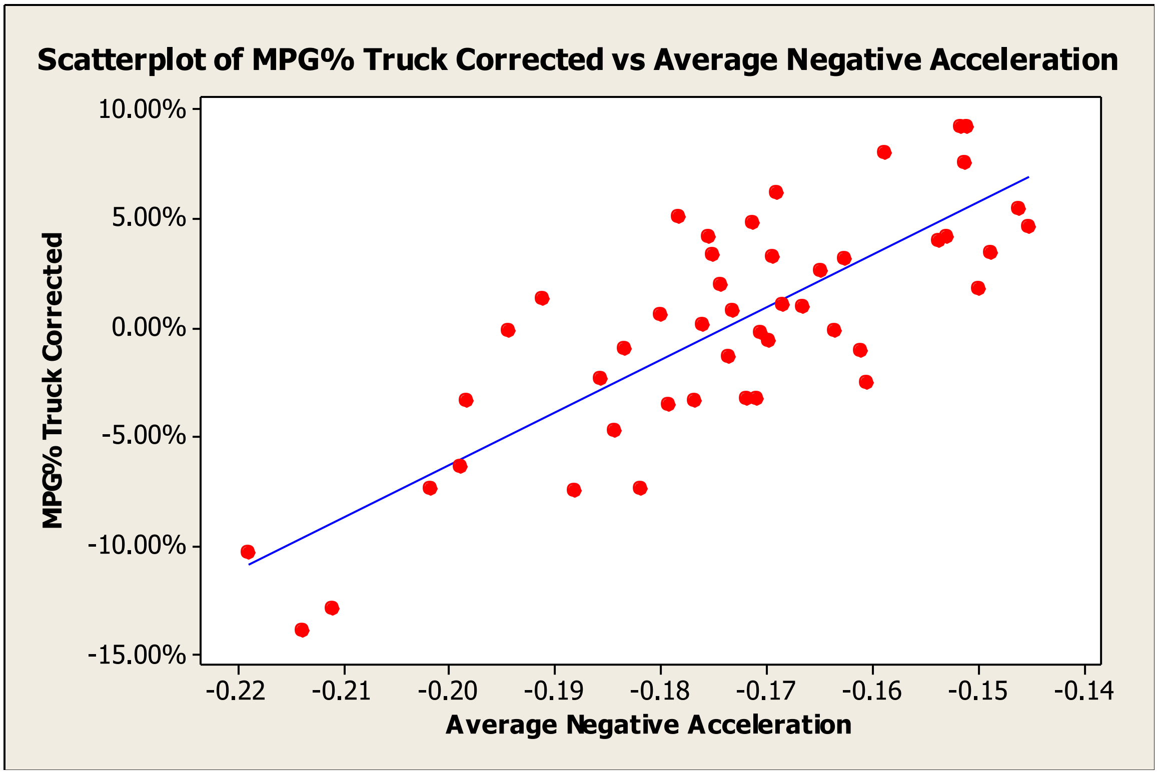


Figure A-2: Correlation between average negative acceleration vs. percent MPG difference from mean.

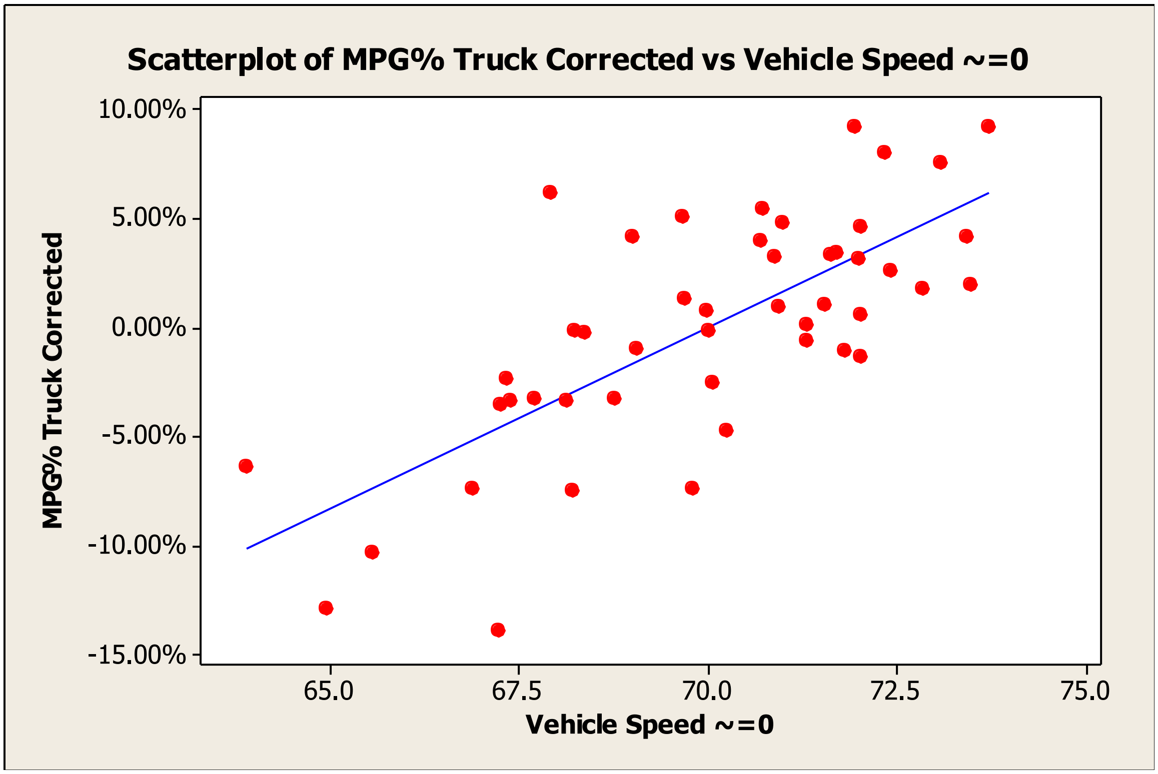


Figure A-3: Vehicle Speed correlation against percent difference MPG from mean

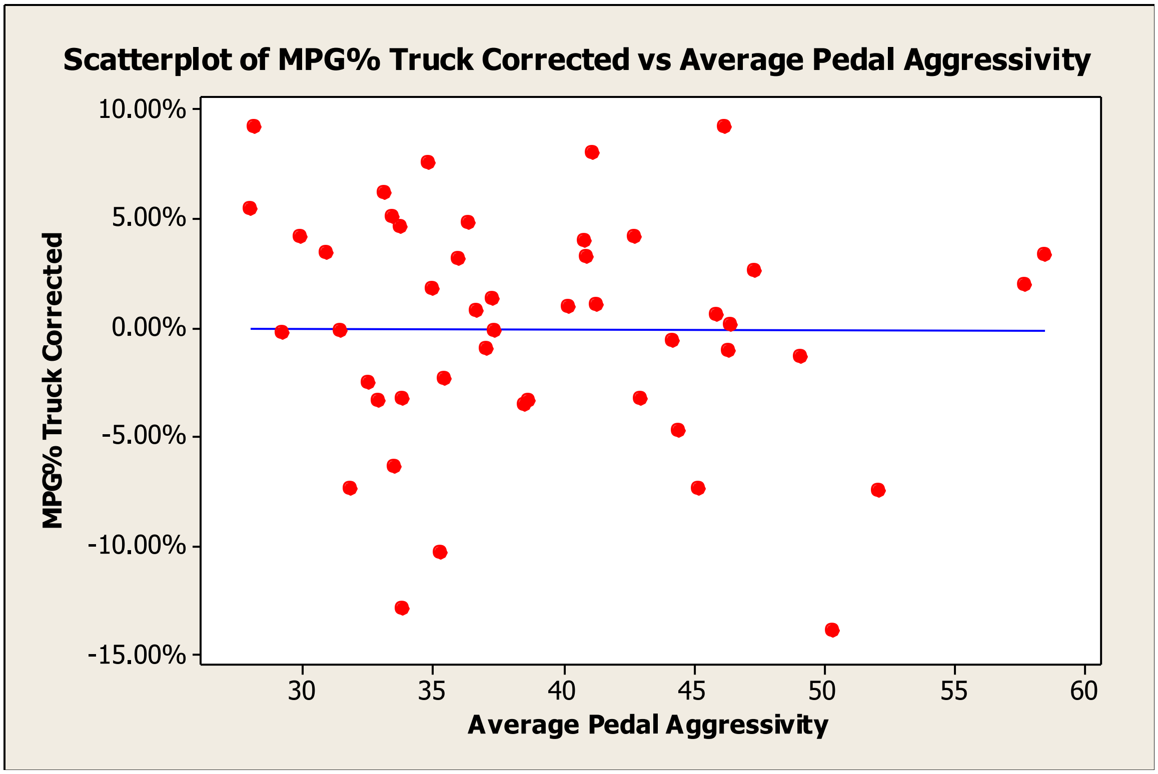


Figure A-4: Average Pedal Aggressivity vs. Percent MPG difference from the mean.

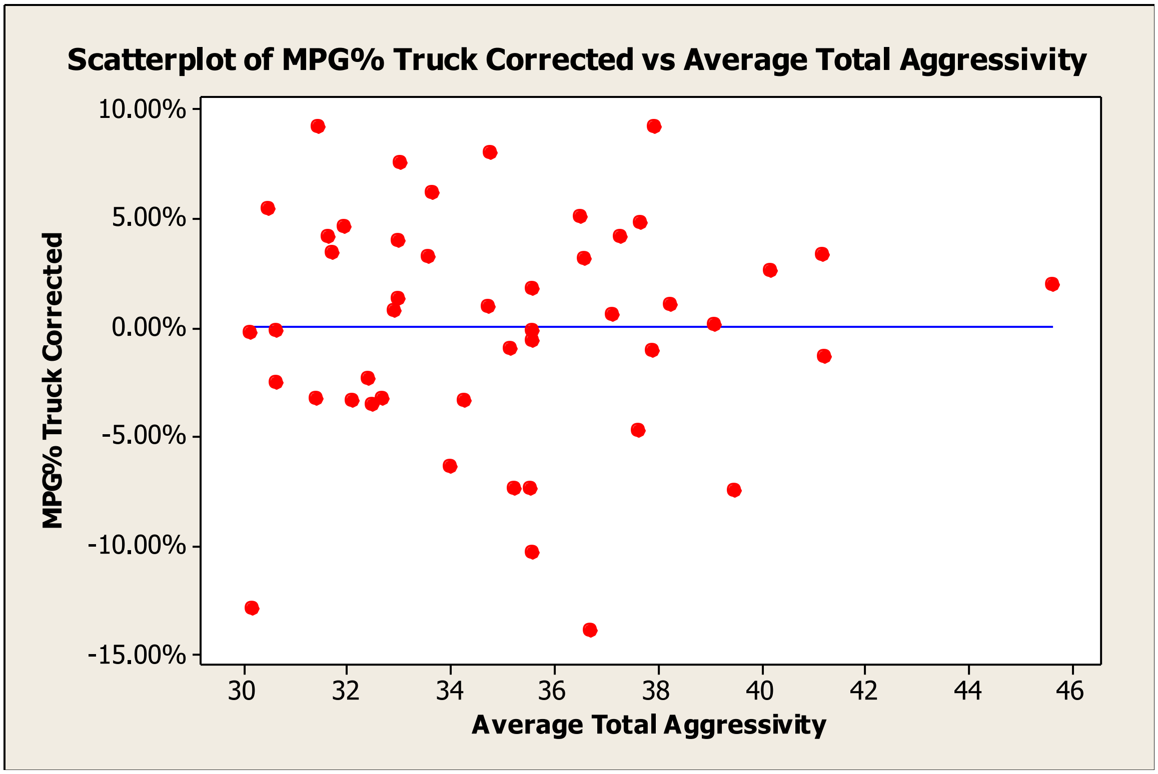


Figure A-5: Correlation between average total aggressivity and percent MPG difference from the mean

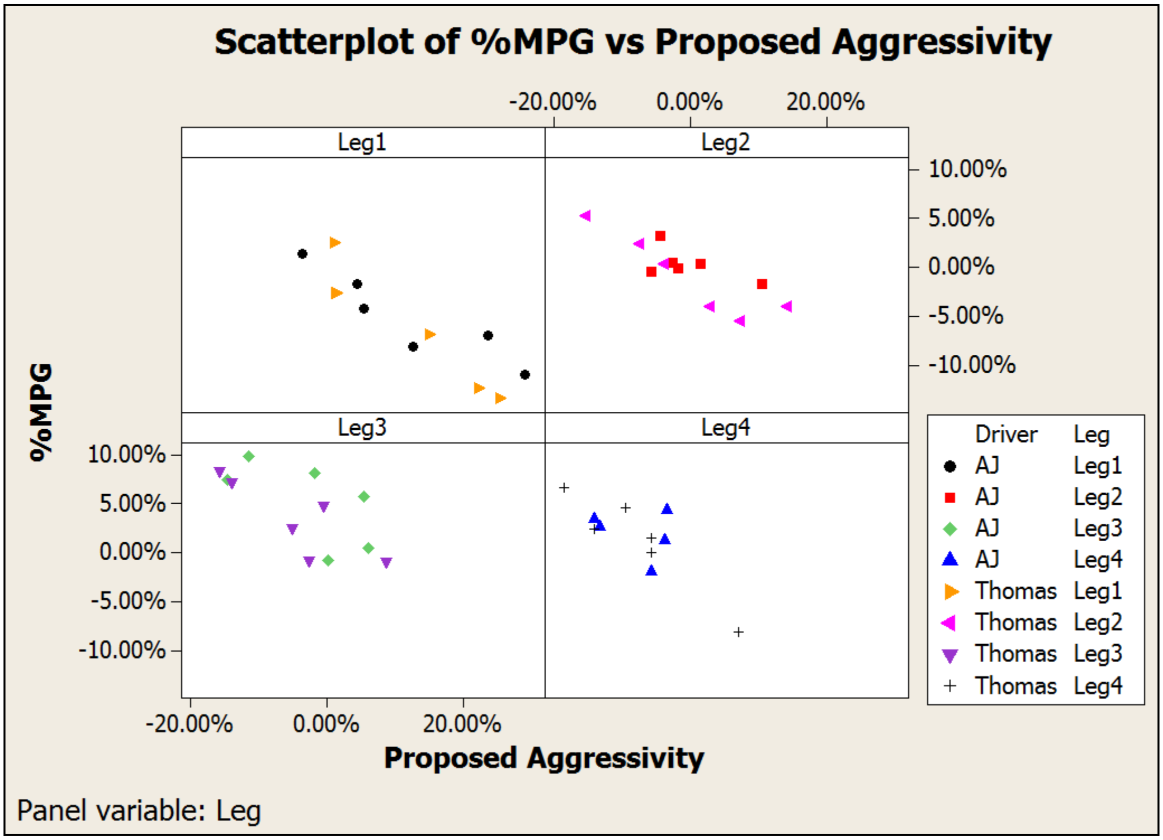


Figure A-6: Comparison of Driver differences on each individual leg with respect to the proposed aggressivity vs. percent difference of MPG compared to the mean.

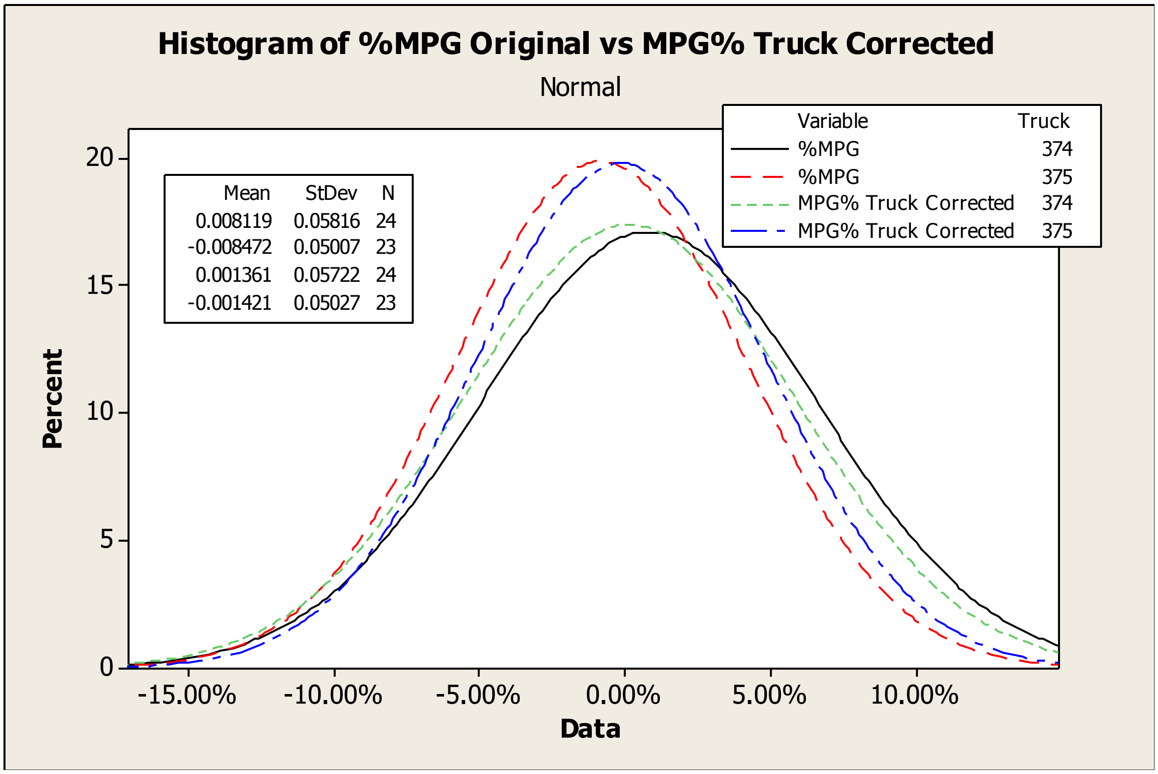


Figure A-7: Impact of correction for truck differences.

Table A-1: Example of calculated data for one truck for one day including all four legs

	374			
	Thomas	AJ	AJ	Thomas
	Leg1	Leg2	Leg3	Leg4
Acceleration Negative	-0.17	-0.17	-0.17	-0.17
Acceleration Positive	0.15	0.16	0.16	0.15
Accelerator Pedal Rate Negative	-10.14	-12.33	-11.77	-10.20
Accelerator Pedal Rate Positive	10.45	10.88	11.41	11.10
Accelerator Pedal Position	22.39	14.68	14.79	17.37
Velocity	59.91	69.47	63.94	67.38
Average Vehicle Aggressivity	312.90	353.39	356.67	314.34
Average Pedal Aggressivity	33.77	47.30	49.06	44.13
Average Total Aggressivity	31.37	40.17	41.23	35.57
Engine Speed	1122.94	1193.70	1169.60	1160.74
Engine Torque	583.46	637.34	576.34	657.18
MPG	7.22	7.66	7.36	7.42
Pedal Position ~=0	49.91	54.78	55.59	49.93
Vehicle Speed ~=0	67.68	72.42	72.01	71.29
Proposed Aggressivity	0.07	0.07	0.07	0.07

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