OWNER RELATED
FUEL ECONOMY IMPROVEMENTS

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1. INTRODUCTION

While the primary focus of fuel conservation has been on the fuel economy of new car and light trucks, it is widely recognized that vehicle owners can take a number of steps to maximize the fuel economy of their vehicle in-use. Of course, major retrofits or design alterations cannot be considered due to prohibitive costs, but there are several low cost actions that vehicle owners can take. Four actions are examined in this report, namely:

- use of fuel efficient lubricants;
- use of low rolling resistance tires;
- performing routine maintenance;
- modifying driving habits.

Of these four, the first two are related to replacement purchases for factory installed oils or tires, while the second two are related to consumer actions and preferences.

Names of these actions are new, but there are a few historic attempts to actually quantify the benefits available to the consumer. Part of the problem has been the lack of hard data especially on the issues of maintenance and driving habits. Studies conducted in the 1990s on these actions and their effect on emissions has opened the possibility to examine fuel economy effects from these same data utilized to examine effects on emissions.

This report summarizes available data or studies to quantify the benefits of appropriate consumer actions to maximize fuel economy. Section 2 examines lubricants. Section 3 examines low rolling resistance tires. Section 4 addresses routine maintenance while Section 5 estimates the impact of aggressive driving. While the individual benefits from any one of these actions is just a few percent, the overall benefits from all actions could be significant.

2. FUEL EFFICIENT LUBRICANTS

2.1 BACKGROUND

Engine oils serve several functions, including reducing friction, cooling the engine, limiting wear on the moving parts of the engine, and protecting against corrosion. It is primarily its effect on friction that impacts fuel economy (FE). Friction is an important cause of energy loss within the vehicle. Engine oils reduce friction in two ways:

- the oil separates opposing metal surfaces to prevent contact (*hydrodynamic lubrication*);
- friction-modifying additives alter metal surfaces so friction forces aren't as great when there is metal-to-metal contact (*boundary lubrication*).

Two-thirds of the friction losses in an engine are estimated to occur during hydrodynamic lubrication and one-third during boundary lubrication or mixed hydrodynamic/boundary lubrication. The new energy-conserving motor oils are designed to reduce friction losses from both types of lubrication by tailoring the viscosity characteristics of the base oil and the chemistry of the friction-modifying additives.

Engine oils are categorized into grades such as 5W-20 or 10W-30.

- 5W refers to fluidity when cold (W = winter grade). The lower the number, the more fluid the oil at low temperatures, making cold starts easier;
- 20 refers to fluidity when hot. The higher the number, the more viscous the oil at high temperatures and the better it protects when hot (motorway).

The other classifications are the API standards:

- API 'S' : petrol engine;
- API 'C' : diesel.

A second method of classifying oils is mineral versus synthetic. In conversations with Castrol and Lubrizol, their staff claimed that synthetic oils offer more durability. Even though neither company specifically recommends driving more than 3,000 miles without an oil change, their staff believes that for longer oil change intervals, it is better to use the synthetic oils, as they do not degrade as quickly as mineral oils. Neither of these companies claims that the synthetics offer any significant FE benefits over similar viscosity mineral oil. Given that most of the literature on the relationship between FE and engine oil only reference mineral oils, these are the focus of this report.

The two major properties of an engine oil that directly influence FE are the oil's viscosity and the presence of friction modifying (FM) additives. The lowest possible viscosity results in the best FE but this choice is constrained by oil consumption and engine durability concerns. In recent years, the viable viscosity of engine oils has fallen significantly. In the 1970s and 1980s the most commonly used grades, SAE 10W-40 and 15W-40, were gradually replaced by SAE 10W-30 and 5W-30 in light-duty engines during the 1980s. Today, the most commonly used factory fill oil in car and light-duty truck engines is 5W-30, although some fraction of consumers continue to use 10W-30 or 10W-40 oil when the oil is changed. More recently, 5W-20 and 0W-20 oils have appeared in the market. 5W-20 oils are now used in many popular cars such as most Honda 2000 and later vehicles and most Ford 2001 and later vehicles as factory fill oil, while 0W-20 is used only in the new Honda Insight hybrid vehicle.

The issue of the manufacturer recommended oil is relevant because the new-car warranty only holds as long as the recommended maintenance procedures are followed, and this includes using the recommended oil. Conversations with lubricant manufacturers have confirmed that it is common practice for the "recommended" oil to be used until the warranty is over. Manufacturers are not explicit in disallowing the use of other oil grades, but are also not explicit about the issue of warranty continuation. Several major manufacturers contacted by EEA conceded that, by and large, 5W-20 oil should be adequate for most modern (post-1995) cars and light trucks, but many manufacturers do not recommend it officially. However, manufacturers specifically cautioned against the use of 5W-20 oils in some high performance vehicles, vehicles subjected to heavy loads or trailer towing, and in very hot ambient conditions (e.g., summer in Arizona).

2.2 FUEL ECONOMY EFFECT OF OILS

There is a large volume of literature on the effect of oil properties on engine friction and on vehicle fuel economy. Much of the literature, however, focuses on specific oil properties and additives, and the literature on the relationship between commercially available oil formulations and vehicle fuel economy is more limited. Most of the current literature compare the benefits of oils using 5W-30 as the reference base, since this oil is the factory fill oil for most light-duty vehicles since the early 1990s. Papers from the early-1980s have compared the performance of 5W-30 oils against 10W-30 and 10W-40 oil, and have found benefits in fuel economy in the 1.2 to 2.0 percent range. In almost all cases, the testing was conducted under standard conditions such as the EPA test or the American Society of Testing and Materials (ASTM) Sequence VIA test. In general, these tests underestimate the benefits of low viscosity oils to the consumer, as they do not involve testing at cold ambients where reduced viscosity benefits can be large. The benefits of 5W-30 oils over 10W-30/40 oils on more modern vehicles are in the same range, as confirmed in a 1995 paper by researchers Korcek and Nakada (from Ford and Toyota, respectively) which summarizes the benefits of alternative oil formulations.

Korcek and Nakada (Ref. 1) also provide preliminary data on the benefits of 5W-20 and 0W-20 oils over 5W-30 oils. Charts in the paper suggest that a fuel economy benefit of one to two percent is possible, although the range shown was large due to differences in friction modifiers between the different oil formulations. A more direct comparison of two commercially available oils performances' on popular vehicles is found in the paper by Tseregounis and McMillan (Ref. 2). The paper indicates that SAE 5W-20 engine oils demonstrate 1.0-2.2 percent (average 1.5 percent) FE gains over the SAE 5W-30 oils on several GM vehicles.

Most concerns with lower viscosity oils are associated with their effect on engine wear. Tanaka et al. (Ref. 3) from Honda address these concerns. They study the impact of using a 0W-20 oil enhanced with a relatively common molybdenum based friction modifier. In their study, they compare the 0W-20 oil to a standard 5W-30 oil, with the same additive blends, both for FE benefit and engine durability. They conducted tests on a Honda engine and a Honda vehicle, and found an impact of 1.5 percent on FE with no significant difference on engine durability. At this moment, 0W-20 oil is only available from select retailers at a price of over $8 per quart, as the Honda Insight is the only car for which this oil is explicitly recommended in the owner's manual.

Kawai et al. (Ref. 4), researchers from Toyota, found that the fuel economy of in-use engines can be improved using SAE 5W-20 oils containing certain friction modifying additives by 1.5 percent on average, when compared with the FE achieved with a conventional SAE 5W-30 oil without these additives. They also found that, in new engines, the FE can be improved with the same SAE 5W-20 oil by 3.5 percent. An improvement of more than 1.5 percent was retained to 10,000 kilometers (relative to a conventional SAE 5W-30 oil). These tests were done on a Toyota vehicle with a 2.2L, 4 cylinder, DOHC engine.

While it need not necessarily apply to all vehicles, it is encouraging that the 1.5 percent fuel economy benefit figure has been found to apply to GM, Honda and Toyota vehicles. Engine designs from these three manufacturers are reasonably representative of the universe of engine designs in modern cars.

2.3 SUMMARY

The use of fuel-efficient oils provides modest benefits to fuel economy at very low cost to the consumer. 5W-30 oil can be used in most 1991 and later vehicles, and can provide a fuel economy benefit of one to two percent relative to 10W-30 oils, more at cold ambient conditions. 5W-20 oil can provide an additional 1.5 percent benefit in fuel economy relative to 5W-30 oil and can be used on a large number of post-2000 models as well as several 1996 to 2000 models. Many manufacturers have provided service bulletins to their dealers on the 1996-2000 engines compatible with 5W-20 oils. In general, caution should be excersized with the use of 5W-20 oils in high performance vehicles, vehicles subjected to heavy loads or vehicles operated in very hot weather. Various brands of both of these oils are available in retail outlets and cost differences between oils of different viscosity range from zero to 50 cents per quart, depending on brand.

REFERENCES FOR SECTION 2

1. Tseregounis and Mcmillan, *FE Gains with Modern Technology, SAE 5W-20 Engine Oils in a GM Engine as Measured in the EPA FTP Test*, SAE Paper 2001-01-1900 2001.

   SAW 5W-20 (GF-3) engine oils demonstrated 1.0-2.2 percent (average 1.5 percent) gains in combined FE over a typical GF-2 quality SAE 5W-30 oil. The vehicles used for the test were two identical 1998 MY Buick centuries equipped with 3.1l engines, and the EPA FTP test was employed.

2. Tanaka, Nagashima, Sato and Kawauchi, *The Effect Of 0w-20 Low Viscosity Engine Oil On FE*, SAE Paper 1999-01-3468, 1999.

   Oil with a high viscosity index and enriched with a molybdenum-based friction modifier was found to offer 1.5 percent FE improvements. FE performance was evaluated using both an engine bench and an actual vehicle. The vehicle was running in the LA-4 mode and used a low friction engine with a roller type valve train. The oil used satisfied the API GF-2 standards.

3. Hoshino, Kawai and Akiyama, *Fuel Efficiency of SAE 5W-20 Friction Modified Gasoline Engine Oil*, SAE Paper 982506, 1998.

   Oil optimized to satisfy FE and anti-wear performance was found to improve FE by 1.5 percent over more than 10,000 km. An unspecified 'popular' Toyota vehicle was used, with a 2.2l I4 DOHC engine, with a bucket type valve train system.

4. Wilk And Newkirk, *Towards Improved FE in Passenger Car Motor Oils: An Investigation into the Influence of Detergent System and Friction Modifier as Measured by the EPA Federal Test Procedure and Highway FE Test Cycles*, SAE Paper 982505, 1998.

   Oils that had been treated with detergents and friction-modifiers were found to offer FE benefits in the 1-4.7 percent range as compared to the currently available GF-2 lubricant, depending on the vehicle and measurement methodology. Five vehicles were used: a 1994 Ford Crown Victoria, a 1998 Toyota Camry, a 1997 Pontiac Grand Am, a 1998 Dodge Caravan, a 1998 Honda Accord and a 1997 Nissan pickup. The EPA FTP cycle was used. Test methods used were carbon balance, fuel flow metering and gravimetric measurement.

5. Lam and McDonnel, *Critical Oil Physical Properties that Control the FE Performance of General Motors Vehicles*, Devlin, SAE Paper 982503, 1998.

   Oils with similar High Temperature High Shear (HTHS) viscosity and pressure viscosity coefficients but with lower boundary friction coefficients were found to offer FE benefits of between 1.3-1.8 percent in gm vehicles. The vehicles used were a Pontiac Grand Am and a Buick LeSabre, the test procedures used were the sequence VIA and VIB.

3. FUEL EFFICIENT TIRES

Most drivers do not pay much attention to the impact of their tires on their car's fuel economy. This is unfortunate, as tires are a significant factor in a car's fuel efficiency. Tires are directly responsible for about 15 percent to 27 percent of typical fuel consumption. They also contribute to aerodynamic and inertia losses, resulting in a total amount of fuel consumption due to tires that may approach 30 percent. It should be noted that this number varies significantly with speed and is highest at highway speeds.

3.1 TIRE DESIGN FACTORS

The tire design contributes to vehicle fuel economy in several ways:

- the tire has a given finite area that creates aerodynamic drag force;
- it has a mass that leads to inertia loss;
- it has rolling resistance that results from a combination of tire-road friction and hysteresis. Hysteresis is a major component of a tire's rolling resistance. As the tire deforms, heat is dissipated in the various components of the tire due to the visco-elastic nature of rubber.

The rolling resistance of tires is usually measured by a laboratory test of a single tire, not with a fuel consumption test on a car. Car tests also have been defined but are not in general use. Despite the detailed specification of the tire rolling resistance test procedures, the reality is that the variety of measurement methods being used with different measuring instruments under different circumstances results in significant variability of results. For this reason, some tire manufacturers do not disclose test results on the rolling resistance co-efficient.

The relationship between rolling resistance and the resulting vehicle fuel economy is also examined in the literature. For passenger cars, the observed relationship is that a five to seven percent reduction in rolling resistance produces a one percent increase in fuel economy (Ref. 1). A report by the Goodyear technical center (Ref. 2) in Luxembourg states that with the tires available today, differences of 15 percent to 20 percent can be found between the rolling resistance of functionally similar tires available in the market. This implies potential fuel savings of two to four percent by appropriate tire choice.

Goodyear's technical center estimates that a ten percent tire weight reduction results in approximately 0.1 percent combined fuel economy gain. Lessening the tread depth and making the tires narrower are all options that will increase fuel economy. The problem is that these options have a performance trade-off that may be unacceptable, including loss of wet grip and skid control reduction.

The 1990s saw the introduction and use of Silica (rubber with the addition of silicate) in tires. It is claimed that using Silica in treads to replace Carbon Black enables rolling resistance to be reduced without a corresponding reduction in wet grip or other tire performance measures. The use of Silica in tread compounds can now be considered standard in Europe, but does not appear to have achieved the same level of market penetration here in the U.S. Silica tires were first introduced by Michelin, and their data shows significant reductions in rolling resistance of up to 20 percent relative to conventional tires depending on Silica content (Ref. 3).

In March 2001, Goodyear announced a new tire technology, BioTRED, that they claim has important environmental advantages as well as "remarkably lower rolling resistance" according to company literature. Goodyear claims that this technology lowers rolling resistance by eight percent while increasing wet grip and also reducing the tire weight by five percent. The tire is being introduced in Europe first and is not due to be launched in the U.S. until late 2001. No price information is available yet, and Goodyear has provided no technical details to substantiate their claims.

An area where there is considerable disagreement between the environmental community and the tire and auto industries is in the market for replacement tires. The Natural Resources Defense Council (Ref. 4) has reported that "The average rolling resistance of replacement tires is about 20 percent higher than that of tires that auto-manufacturers use on new vehicles." Marvin Bozarth, the executive director of the International Tire and Rubber Association, states that this is not the case. He said that there may be a slight differential due to the fact that auto manufacturers are significantly more strict about tires being exactly balanced, whereas tire retailers may be less picky. Since manufacturers do not specify rolling resistance, there is no confirmation of the NRDC claim. However, there is acknowledgement in the industry that some low-cost, private brand tires for the replacement market do have significantly higher rolling resistance relative to new car tires.

The alignment and inflation pressure of tires has a significant impact on their rolling resistance, and these topics are covered below.

3.2 TIRE INFLATION

In August 2001, the U.S. Department of Transportation's National Highway Traffic Safety Administration (NHTSA) released the results of a survey (Ref. 5) that showed that many tires on passenger vehicles are under-inflated. This survey, carried out at gas stations around the country, collected data on 11,530 passenger vehicles (cars, SUVs, vans and pickup trucks). Data was collected on vehicles with P-metric tires and 'Other Tires', where P-metric tires are regular passenger car tires, while 'other tires' include LT tires (for light trucks) and High Flotation tires. The data for 'other tire' types was not analyzed due to the small sample size, leaving over 10,000 P-metric tire equipped vehicles in the survey. The observations were weighted to represent the national vehicle population using registration data.

Every tire comes with a recommended cold tire inflation pressure (measured in pounds per square inch). If the tire's measured inflation pressure is below the recommended value, it is considered as under-inflated. Table 3-1 lists the survey's findings. More than one in four of the passenger cars with P-metric tires had at least one tire under-inflated by 8 psi or more. For pickups, vans and SUVs with the P-metric tires, almost one in three had at least one tire under-inflated by 8 psi or more. The percentage of vans, SUVs, and pickup trucks with all four tires under-inflated by 8 psi or more was twice that of cars with under-inflated tires, as shown in the table below.

TABLE 3-1
RESULTS OF TIRE INFLATION SURVEY

	No. of Tires under-inflated by >8 PSI				
VEHICLE TYPE	0	1	2	3	4
Passenger Cars with P-metric tires	73	14	7	3	3
Pickups, SUVs and Vans with P-metric Tires	68	13	10	4	6

The following chart supplied by Goodyear gives an indication of how under-inflated tires translate into fuel economy impacts. This chart is for an example tire with a recommended pressure of 38 psi, and it shows the fuel economy decline with under-inflation. The fuel economy decrease is approximately linear with under-inflation pressure, and inputs from tire manufacturers suggest that the functional relationship is quite similar for tires with slightly different recommended pressure. The majority of P-metric tires have recommended inflation pressures of 28-34 psi. Taking 32 psi as a typical recommended inflation pressure, and assuming that the results displayed in Figure 3-1 are also typical, implies that 8 psi under-inflation results in a 3.3 percent decrease in MPG.

3.3 SUMMARY

In-use fuel economy of passenger cars and light trucks can be influenced by tire choice and by keeping tires properly inflated. By choosing a fuel efficient tire model, consumers can reduce rolling resistance by up to 20 percent, which can provide a fuel economy benefit of up to four percent, depending on the speed and driving cycle. Currently, tires are not labeled for rolling resistance or fuel efficiency, but several manufacturers have agreed to provide information on the most fuel efficient choice of tire within the models available for a given brand. In addition, small but significant improvements in fuel economy can be realized by keeping a tire properly inflated to the recommended value. For every 1 psi drop in the pressure of all four tires, fuel economy declines by 0.3 percent. Survey data by NHTSA shows that about a third of the fleet has at least one tire severely under-inflated, suggesting significant potential for fuel economy improvement.

REFERENCES FOR SECTION 3

1. Sovran, G. and Bohn, M., *Formulae for Tractive Energy Requirements for Vehicles Driving the EPA Schedule*, SAE Paper 810184, 1981.

2. Junio, M., Roesgen, A. and Corvasce, F., *Rolling Resistance of Tires*, Goodyear Technical Center Paper, Luxembourg, 2000.

3. Michelin, Presentation to the US DOE, June 2000.

4. NRDC, information on website. For passenger cars, the observed relationship is that a 5 to 7 percent reduction in rolling resistance produces a one percent increase in fuel economy.

4. EFFECT OF MAINTENANCE ON FUEL ECONOMY

4.1 OVERVIEW

Despite the fact that many information sources, including the EPA web site, state that a well-tuned vehicle will be more fuel efficient than one in need of maintenance, justification for this statement in the form of peer reviewed analysis seems to be largely unavailable. Conversations with an official at EPA's Office of Transportation and Air Quality (OTAQ) have indicated that this knowledge has just been 'picked up along the way'. Lacking adequate technical literature, EEA has carried out an analysis using EPA data on vehicles tested before and after maintenance in an attempt to quantify the potential impact.

The EPA data utilized was collected between the years 1990 to 1993 in Indiana and Arizona. The purpose of the study was to compare the emission factors derived from the traditional Federal Test Procedure (FTP) emissions test and the newly developed Inspection/Maintenance IM240 procedure. In order to facilitate the comparison, emissions data using both test procedures were collected from over 800 cars and light-duty trucks. When a vehicle was found to be in violation of the emission standards applicable, repairs were carried out. Fortuitously, the FTP tests conducted for the study also included measurements of fuel economy (FE) in miles per gallon (MPG) for the pre- and post-repair tests. This portion of the study was done on the FTP urban driving cycle, that is representative of typical city driving with an average speed of about 20 mph.

If a vehicle's emissions for the three key pollutants were below the applicable standards, then no repairs were performed, and there is no post-maintenance data. Although over 800 vehicles were tested, a total of 422 vehicles had maintenance/repairs carried out. As an initial estimate of the effect of maintenance on FE, a simple average percentage improvement in FE for all vehicles with pre- and post- repair data was calculated, and this gives a result of a 6.4 percent increase in

MPG. The distribution of the change in fuel economy is displayed in Figure 4-1. As can be seen there is a wide spread of resulting changes in FE, from –minus 40 percent to plus 120 percent.

The direct use of the EPA data is not recommended for several reasons. First, data from any testing program usually has some errors due to in correct tests or in correct data entry. Second, the repairs were not always correctly performed and some vehicles were subjected to multiple repairs. Third, the tested sample of vehicles includes many from older model years, when engine technology was significantly different from technologies employed in current vehicles. In order to refine this result several steps were taken.

4.2 DATA ANALYSIS

In order to make the data more relevant to the vehicles on the road today, all of the vehicles older than model year 1985 were filtered out. Starting in 1985, electronic fuel injection was widely introduced into mass production models as a response to tighter emission regulations (replacing the carburetor) and fuel injection is used in virtually all cars and light trucks today. The post 1984 sample of vehicles with pre- and post-maintenance is 238, and a corresponding average increase in FE after maintenance is 6.6 percent.

As can be clearly seen in Figure 4-2, there is still a very wide spread in the resulting changes in FE, from +120 percent to almost -30 percent in the post-1984 vehicle sample. Very large decreases in fuel economy as a result of maintenance are known to be impossible if the repairs are correctly performed. Large increases in fuel economy are possible only in cases where the vehicle was in very poor condition or had fuel leaks prior to repair. A small decrease in FE is, however, plausible, in cases where the adjustments made to the vehicle are for the purposes of correcting certain types of emission problems. Engineering analysis suggests that the limits of plausibility are a decrease in FE of over 20 percent and an increase of over 40 percent. Records showing changes outside this range are almost certainly due to measurement or reporting errors, and were removed from the data.

FIGURE 4-1
DISTRIBUTION OF CHANGES IN FUEL ECONOMY FROM REPAIRS
(raw data from EPA)

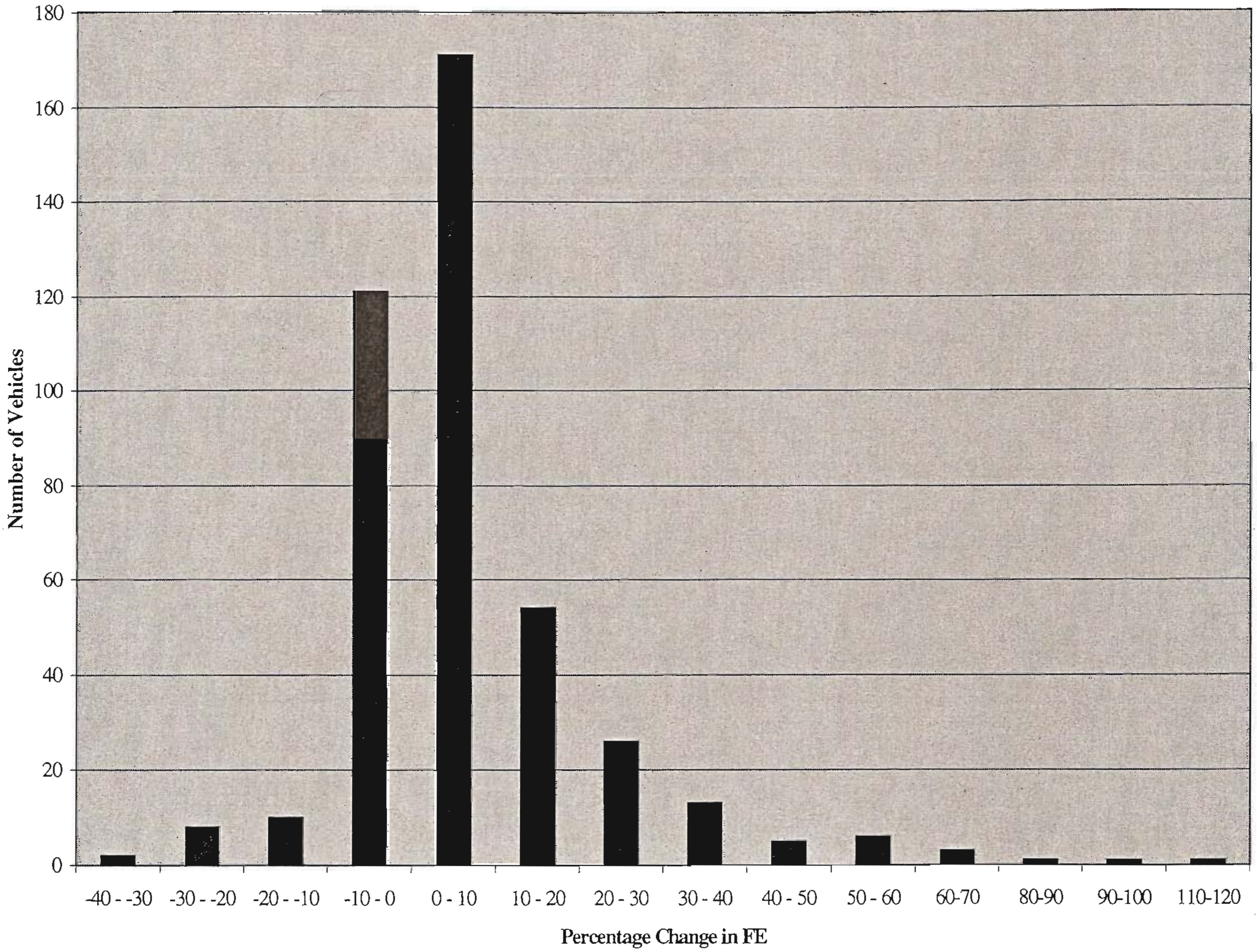
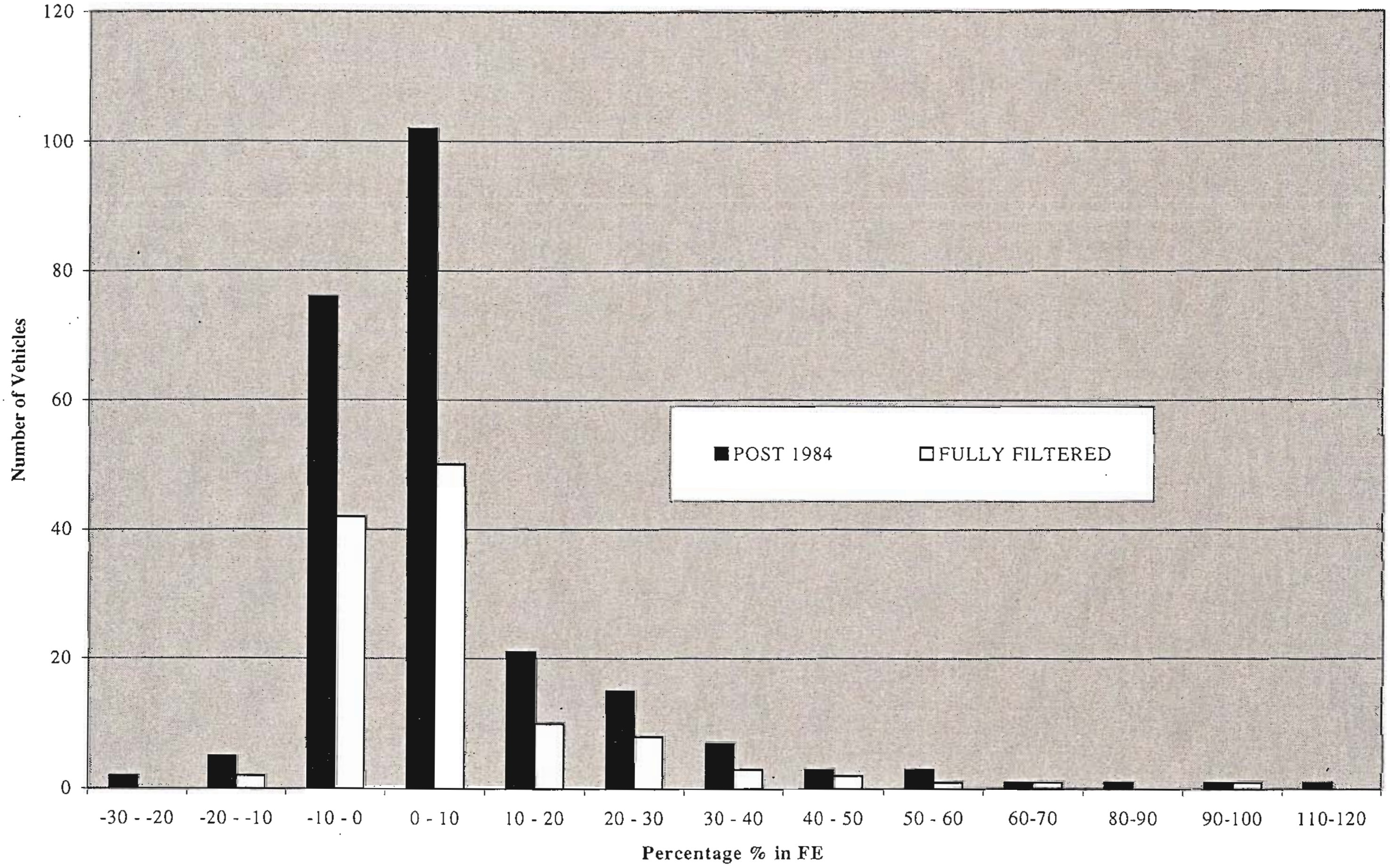


FIGURE 4-2
DISTRIBUTION OF CHANGES IN FUEL ECONOMY FOR MY1985+ VEHICLES
(before and after filtering for potentially erroneous data)



To account for the incorrect repairs, data indicating that the vehicle failed to reduce emissions to levels that were within 1.5 times the applicable standards for any pollutant after the repairs were carried out were also filtered out.

Of this filtered sample of 116 vehicles, 71 exhibited an increase in FE of an average of 8.9 percent, while 45 exhibited a drop in FE as a result of maintenance, with an average decrease of 3.5 percent. The ratio of number of positive changes to negatives gives an estimate of the probability that maintenance conducted to meet emission standards will increase FE; i.e., 71:45, or over 3:2.

An analysis of the types of repairs causing significant decreases in fuel economy was also completed. Seventeen vehicles had fuel economy declines of greater than five percent (smaller declines can be a result of test-to-test variability). Of these seventeen, ten had problems with the exhaust gas re-circulation (EGR) system, and twelve had high NOx emissions before repair. Five others had repairs of ignition timing. Hence it appears that EGR and timing related repairs account for most of the fuel economy declines, and the decline is consistent with engineering analysis.

A similar analysis of vehicles showing large increases in fuel economy after repair also showed one type of problem to be dominant. Of seven vehicles reporting fuel economy increase of over 40 percent, six had failures of the oxygen sensor. It appears that this type of failure caused the fuel system to operate at very fuel rich conditions. Engineering analysis also indicates that repairs of such failures can lead to large increases in fuel economy

4.3 SUMMARY

This analysis provides the following conclusions:

- if a modern vehicle fails an emissions test, then it stands a better than 3:2 chance of improving its FE after proper maintenance;
- if the vehicle experiences an increase in FE after repair, the expected increase is almost nine percent;

- if the FE decreases as a result of the repairs, then the expected decrease is about 3.5 percent. Decreases in fuel economy are typically associated with repairs of the EGR system or ignition timing changes to remedy high NO_x emissions;
- if the vehicle is in very poor condition prior to repairs then significant increases in FE are possible. Large increases are possible if the fuel system has failed at a rich air-fuel setting, and such failures are typically associated with faulty oxygen sensors;
- the net expected value of the change in FE as a result of repairs is 4.1 percent.

This study did not include any repair cost data, but given that meeting emission standards is a requirement for registering a vehicle in most states, repair cost may not be a factor under vehicle owner control.

5. THE EFFECT OF AGGRESSIVE DRIVING ON FUEL ECONOMY

5.1 BACKGROUND

It is widely known that the manner in which a car is driven will impact its resulting fuel economy, and that driving with hard accelerations and decelerations will result in a fuel-economy penalty. Such general information is provided on the EPA website, and can be found in many other sources of fuel economy information, and yet, there has been little in the way of reliable quantification of these claims.

A first step in any quantification is to define 'aggressive' driving. This is usually taken to mean high rates of acceleration, deceleration and high speeds. Historically, there has been limited investigation of the effect that some of these driving modes have on fuel economy. In 1980, Jones (Ref. 1) quantified the effects of acceleration rates on fuel consumption by measuring fuel consumed over one mile with specified acceleration rates ranging from one to five miles per hour per second (mph/sec). His findings were that fuel consumption increased approximately linearly with an increasing acceleration rate. Hooker's work from 1985 (Ref. 2) examined fuel-efficient driving strategies. His quantitative findings may be dated now, but the most striking finding was the remarkable lack of consistency from car to car.

The problem with isolating one driving mode such as acceleration is that the information produced is not very useful to a driver. In order to evaluate all of the modes that compose 'aggressive' driving, a driving cycle must be defined. The cycle is a set pattern of speed, acceleration, and deceleration with time or distance that can be defined to reflect some types of real world driving under specific conditions.

Despite the lack of recent interest in the relationship between driving cycles and fuel economy, environmental organizations have become interested in the driving cycles – emissions relationships. The investigation of this relationship has led to the EPA and CARB developing driving cycles that represent more aggressive driver behavior and examining the resulting emissions. Data from tests of vehicles on these cycles as well as the more standard driving cycles can be used to compute the effect of driving behavior on fuel economy. These resulting fuel economy figures can also be used in conjunction with the parameters of the driving cycles to investigate the relationship. The EPA and CARB have provided EEA with emissions data from cars tested on several driving cycles.

5.2 DATA AND ANALYSIS

Concern that the standard Federal Test Procedure's urban and highway cycles failed to capture the effect of more aggressive drivers on measured vehicle emissions led the ARB to develop a new cycle called the Unified Cycle. In 1996, as part of their program to evaluate the 'Unified Cycle' (UC), CARB carried out an emissions study on 17 vehicles, comparing the emissions under this cycle to those produced by the same vehicles under the Federal Test Procedure (FTP) city cycle. The UC is intended to represent aggressive city driving, with high rates of acceleration and deceleration, high maximum speeds but low average speeds, while the FTP (city) is a more conservative urban driving cycle, with starts and stops but lower acceleration and deceleration rates.

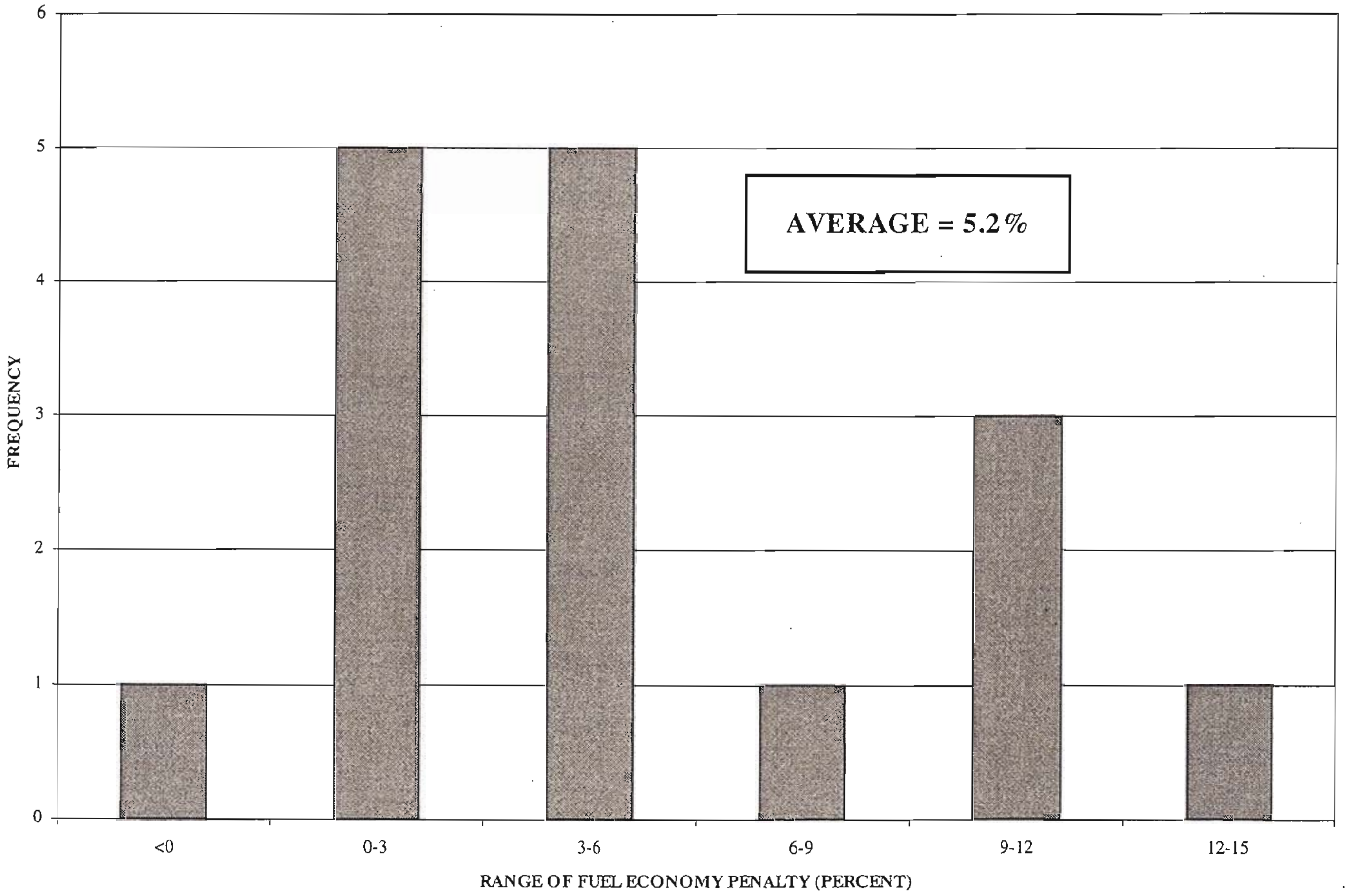
The key parameters of both cycles are presented in Table 5-1. The cycles are similar in their average and maximum speeds. However, the UC is significantly more aggressive in other respects. The UC's average acceleration exceeds the FTP(city)'s by 30 percent, while the maximum acceleration and deceleration are both over 100 percent greater.

TABLE 5-1
PARAMETERS FOR FTP AND UC DRIVING CYCLES

	FTP (CITY)	UC
Average Speed (mph)	21.18	24.63
Maximum Speed (mph)	56.70	67.20
Average Acceleration (mph/sec)	0.89	1.15
Maximum Acceleration (mph/sec)	3.30	6.90
Maximum Deceleration (mph/sec)	-3.30	-8.80

Fuel Economy data on the 17 vehicles tested over the two cycles showed that the fuel economy on the UC was significantly lower than that on the FTP. It is worth noting that all but one of the vehicles exhibited a decline in fuel economy on the UC cycle, with a maximum of a 14 percent decrease and an average of a five percent decrease in fuel economy on the UC relative to the FTP. Figure 5-1 shows the fuel economy decline relative to the FTP for the UC driving cycle for the 17 cars.

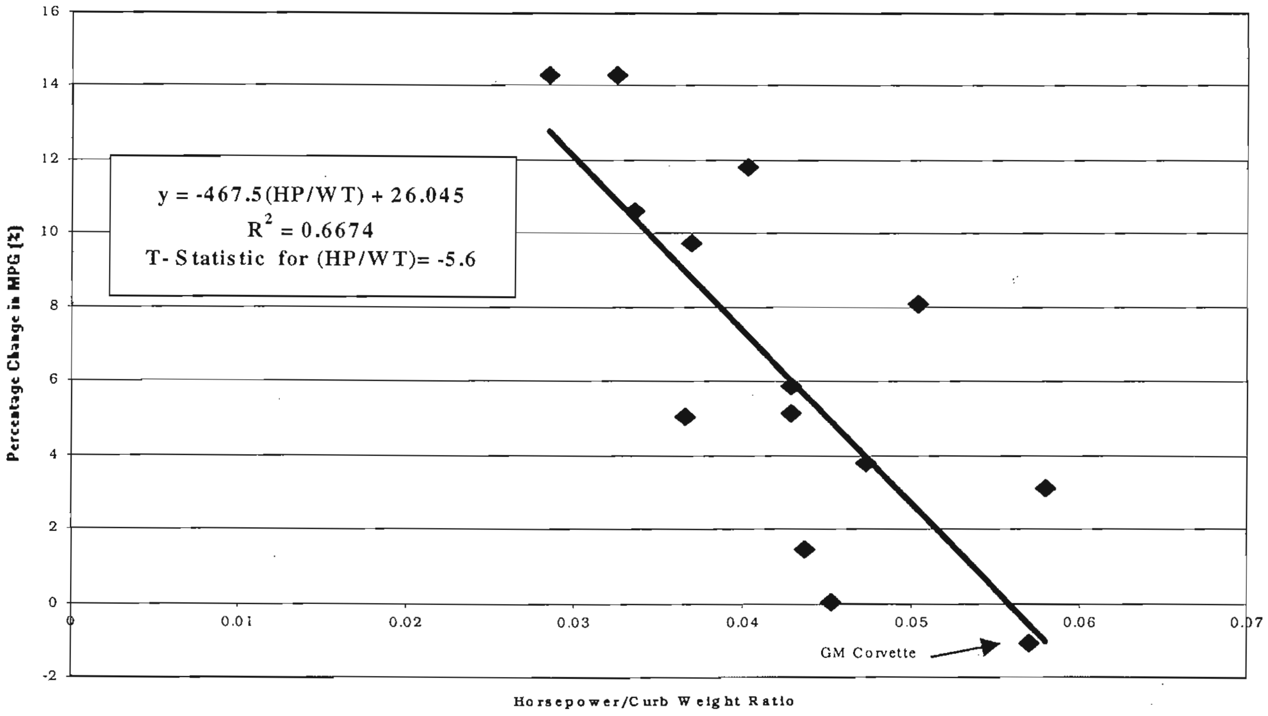
FIGURE 5-1
FUEL ECONOMY PENALTY ON THE UC RELATIVE TO THE FTP(CITY)



The data in Figure 5-1 shows there is considerable car-to-car variation in response, consistent with previous findings. Only one car of the 16 exhibits a decrease in fuel economy on the FTP relative to the UC, a 1982 GM Corvette, while all of the others experience an increase, with the greatest being over 14 percent.

Rather than being random variation, this range of fuel economy impacts are directly related to the power of the cars, more specifically to the horsepower/curb weight (HP/WT) ratio. The HP/WT ratio was calculated for each car in the sample, and the fuel economy penalty was found to be related to the ratio. The results, presented in Figure 2 below, imply that for a powerful (HP/WT ratio over 50 HP per 1000 lbs) car, the fuel economy penalty for aggressive urban driving is minimal, but for those cars with a lower HP/WT ratio, the penalty can be significant. For a typical family sedan whose HP/WT ratio is around 0.04, it appears that aggressive driving at city speeds causes a 6 percent fuel economy penalty.

FIGURE 5-2
FUEL ECONOMY PENALTY AS A FUNCTION OF HP/WT RATIO



Another pair of driving cycles that were developed for emissions testing facilitate an analysis of the fuel economy impacts of aggressive driving at higher speeds. The FTP highway cycle (FTP(hwy)) was developed in the early 1970s to be representative of driving on suburban roadways or expressways. The US06 cycle was developed in the mid-1990s by observing actual drivers and building a cycle to resemble the driving attributes of the 15 percent 'most aggressive' drivers, where 'aggressive driving' is characterized by high rates of acceleration, deceleration and high maximum and average speeds. The attributes of these two cycles are presented in Table 5-2. Graphical representations of these two cycles are provided in Appendix A.

TABLE 5-2
PARAMETERS FOR FTP(HIGHWAY) AND US06 DRIVING CYCLES

	FTP (HWY)	US06
Average Speed (mph)	48.27	48.37
Maximum Speed (mph)	59.90	80.30
Average Acceleration (mph/sec)	0.384	1.383
Maximum Acceleration (mph/sec)	3.20	8.40
Maximum Deceleration (mph/sec)	-3.30	-6.90

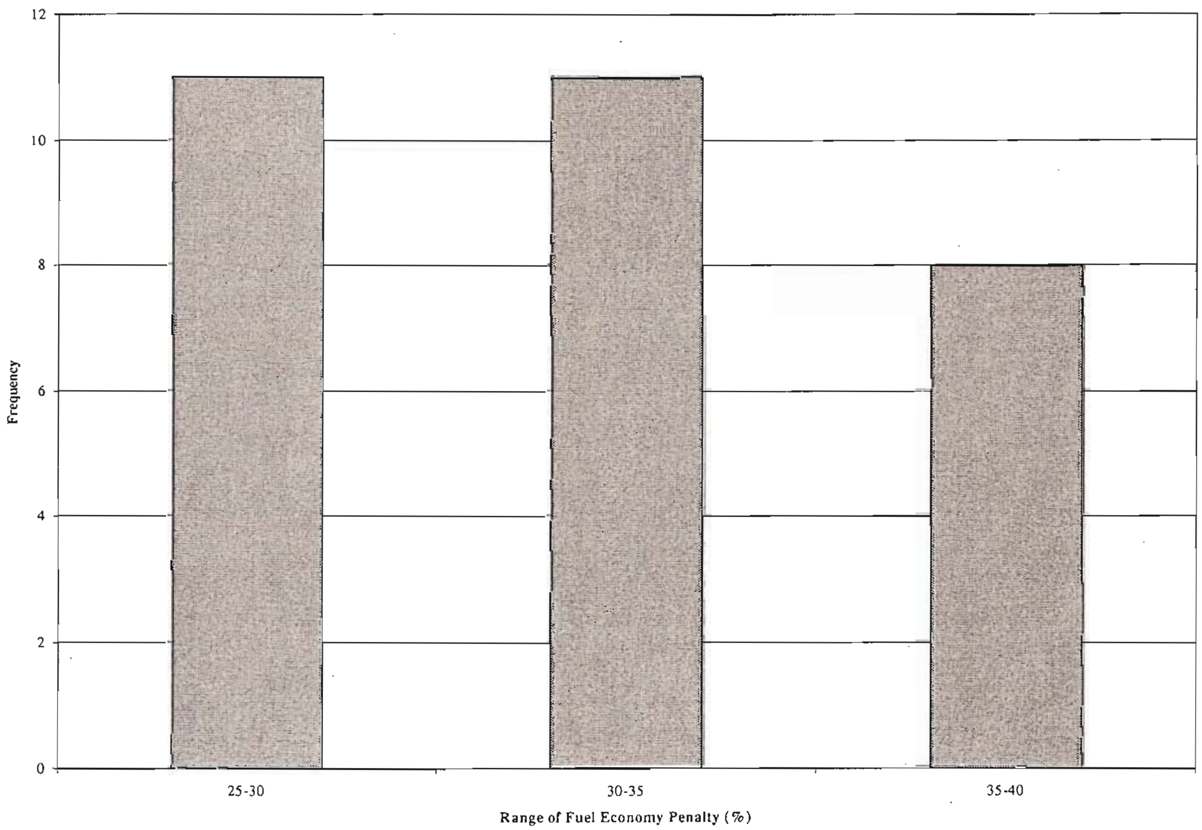
Table 5-2 shows that the US06 is 'more aggressive' than the FTP-HWY cycle on several measures, although the average speed is virtually identical:

- the maximum speed is over 30 percent higher,
- the average acceleration rate is over 300 percent higher,
- both the maximum acceleration and deceleration rates are over 100 percent higher.

EPA tested a relatively large sample of cars on the US06 and FTP city driving cycles, but not the FTP highway cycle. The vehicle specifications (engine/transmission) were incomplete in the EPA data base and the FTP highway cycle official fuel economy value could not be directly determined. Instead, EEA matched the city cycle fuel economy value to the test car list value within 0.5 mpg and used the test car list based highway fuel economy as the appropriate value for each vehicle. This process resulted in matched US06 and FTP highway values for 30 cars.

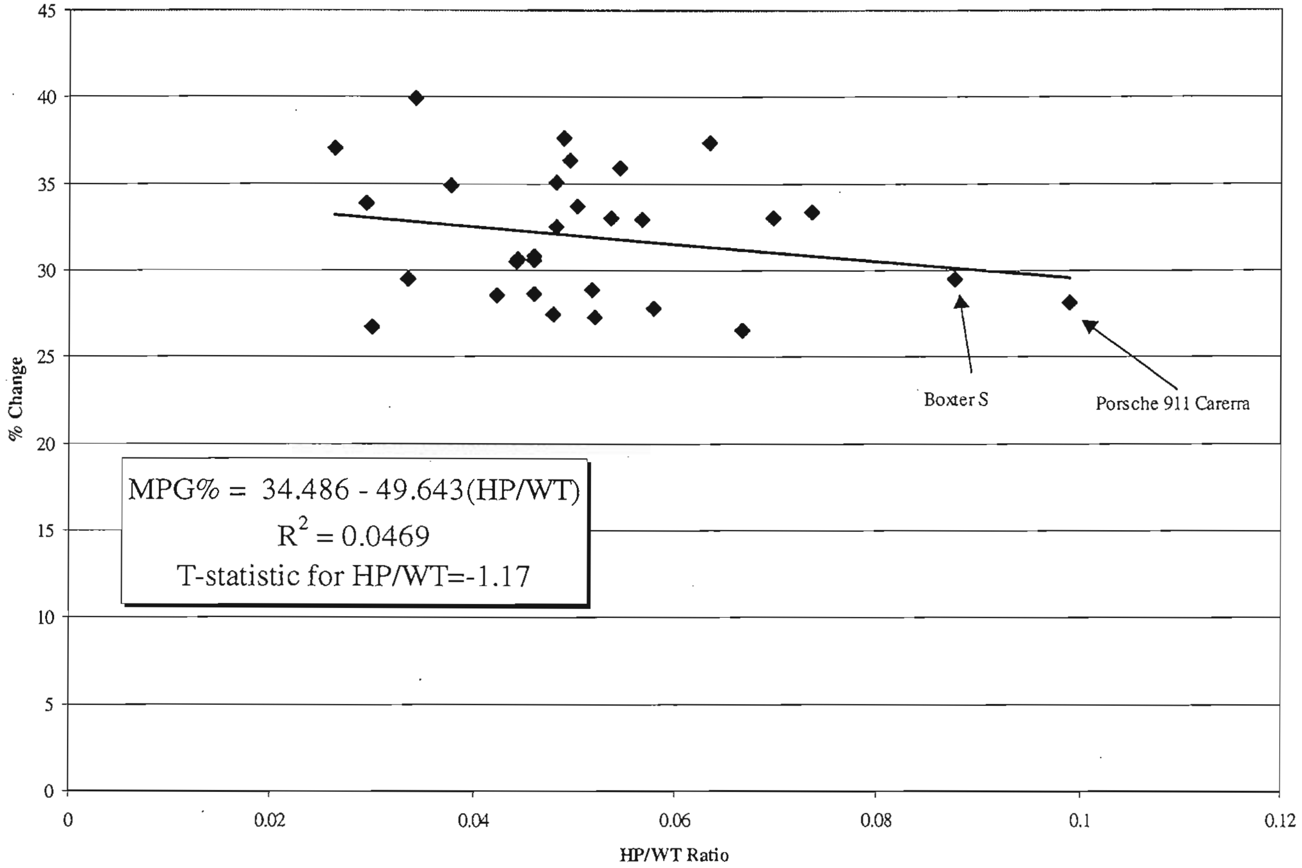
The observed changes between the measured US06 fuel economy and the official highway fuel economy test value for the sample are presented in Figure 5-3. All of the cars exhibit a large decrease in fuel economy, ranging from 25 percent to as high as 48 percent when driven on the US06 cycle, as compared to the fuel economy on the FTP highway.

FIGURE 5-3
FUEL ECONOMY PENALTY US06 VS FTP(HWY)



In order to test the hypothesis that there is a relationship between the horsepower/weight ratio and the percentage change in fuel economy, EEA conducted a regression analysis with the results presented in Figure 5-4.

FIGURE 5-4
FUEL ECONOMY PENALTY VERSUS HP/WT RATIO



Although no statistically significant results were obtained, the trend line is as would be expected: more powerful cars showing smaller losses in fuel economy, (i.e., the powerful cars cope with the more aggressive driving cycles with lower loss of fuel economy), while the less powerful cars suffer greater losses in fuel economy. The lack of statistical significance may be due to the fact that that the FTP highway values are not measured values for the particular car, but the official test value for the model line. Due to car-to-car variability, the actual highway fuel economy for the test vehicle can be significantly different from the official value.

5.3 SUMMARY

The conclusions that can be drawn from this analysis are that at slower speeds typical of city driving, the impact of aggressive driving on fuel economy varies greatly depending on the attributes of the car in question. Very powerful cars exhibit negligible fuel economy penalties, while an average car is likely to experience a penalty of about six percent. At higher speeds, typical of urban expressway driving, however, the fuel economy penalty of aggressive driving is both significant in magnitude and more consistent across all cars. The average car is likely to experience a penalty of 33 percent, with more powerful cars experiencing a somewhat lower penalty of about 28 percent. Hence, the impact of aggressive driving seems to be especially large at high speeds.

REFERENCES FOR SECTION 5

1. R. Jones, EPA Technical Report, *Quantitative Effects of Acceleration Rate on Fuel Consumption*, 1980
2. J. Hooker, Memo To David Green, *Fuel-Efficient Driving Strategies*, 1985.
3. California Resources Board Emissions Data 1994-1998, provided to EEA from CARB.
4. EPA Emissions Test Data 2000-2001, provided to EEA from EPA.