The Effects of Driving Style and Vehicle Performance on the Real-World Fuel Consumption of U.S. Light-Duty Vehicles

by
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Abstract

Even with advances in vehicle technology, both conservation and methods for reducing the fuel consumption of existing vehicles are needed to decrease the petroleum consumption and greenhouse gas emissions of the U.S. light-duty vehicle fleet. One way to do this is through changes in driving style, specifically through reductions in driving aggressiveness. The role of vehicle performance is particularly interesting because of the recognized tradeoff between vehicle performance and certified fuel consumption and because more powerful vehicles are capable of more aggressive driving. This thesis analyzes the effects of driving style and vehicle performance on the real-world fuel consumption of conventional vehicles though two parts.

First, vehicle simulations assess the sensitivity of fuel consumption to a wide range of driving patterns. From these results, three aggressiveness factors were developed for quantifying driving aggressiveness. Each aggressiveness factor, although based only on the speed trace and vehicle characteristics, is proportional to fuel consumption in one of three specific speed ranges: neighborhood, city, or highway speeds. These aggressiveness factors provide a tool for comparing drive cycles and evaluating the real-world driving patterns.

Second, driving data from two U.S. sources was used to 1) provide illustrative examples of real-world driving and 2) assess the relationship between driving aggressiveness and vehicle performance. The distribution of aggressiveness among the driving data follows a lognormal shape. The average aggressiveness is either below or near the aggressiveness of the U.S. drive cycles developed in the 1990s. Moderate performance vehicles, the most common type of vehicle, are driven most aggressively. Low performance vehicles are driven least aggressively.

The results suggest that, for the illustrative data analyzed in this work, reducing velocities during highway driving would save roughly the same amount of fuel as reducing accelerations during all driving. However, on an individual basis, the fuel savings achieved from these behaviors would vary significantly. Aggressive drivers should focus on reducing accelerations, while less aggressive drivers should focus on driving at lower speeds on the highway. And the greatest fuel savings can be attained if the most aggressive drivers, those who drive moderate performance vehicles, drove with lower accelerations.

Thesis Supervisor: John Heywood
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Abbreviations and Symbols

a	Vehicle acceleration (m/s^2)
A	Coastdown coefficient for rolling and drivetrain resistance (N)
A_F	Frontal area of the vehicle (m^2)
AF_{City}	City Aggressiveness Factor (m/s^2)
$AF_{Highway}$	Highway Aggressiveness Factor (m/s^2)
$AF_{Neighborhood}$	Neighborhood Aggressiveness Factor (m/s^2)
ANL	Argonne National Laboratory
ARB02	Air Resources Board drive cycle No.2
B	Coastdown coefficient for rolling and drivetrain resistance (N·s/m)
C	Coastdown coefficient for aerodynamic drag (N·s2/m2)
CAFE	Corporate Average Fuel Economy
CAN	Controller Area Network
C_D	Coefficient of drag
CID	Engine Size in Cubic Inch Displacement (in^3)
CO_2	Carbon dioxide
C_r	Coefficient of rolling resistance for the vehicle,
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
E	Energy (Wh)
ECE	Economic Commission of Europe drive cycle
EIA	Energy Information Administration
EPA	U.S. Environmental Protection Agency
EUDC	Extra Urban Driving Cycle
FC	Fuel Consumption (L/100km)
FHWA	Federal Highway Administration
FTP	Federal Test Procedure
g	Gravitational acceleration (9.81 m/s2)
GHG	Greenhouse gas
GPMR	Gallons per mile ratio
HP	Engine horsepower (hp)
HWFET	Highway Fuel Economy Test
IEA	International Energy Agency
INRETS	Institut de Recherche sur les Transports et leur Sécurité
ITF	International Transport Forum
LA92	Drive cycle based on LA driving in 1992 (also preferred to as the UC)
LDV	Light-duty vehicle
M	Vehicle test mass (kg)
MOVES	MOtor Vehicle Emission Simulator

MPG	Miles per gallon
MY	Model year
NEDC	New European Drive Cycle
NHTS	National Household Travel Survey
NHTSA	National Highway Traffic Safety Administration
OECD	Organization for Economic Co-operation and Development
P	Tractive power (kW)
PEMS	Portable emission measurement systems
PERE	Physical Emission Rate Estimator
PSAT	Powertrain System Analysis Toolkit
REP05	Representative drive cycle No.5
RTECS	Residential Transportation Energy Consumption Survey
SAFD	Speed-acceleration frequency distribution
SC03	Air conditioning drive cycle
SFTP	Supplemental FTP
t	Time (seconds)
$t_{0\text{-}60mph}$	0-60 mph acceleration time (seconds)
UC	Unified cycle (also preferred to as the LA92)
UDDS	Urban Dynamometer Driving Schedule
US06	High speed, high acceleration drive cycle
v	Vehicle speed (m/s)
VSP	Vehicle specific power (kW/kg)
VTTI	Virginia Tech Transportation Institute
W_{wheel}	Wheel work (Wh/km)
WT	Vehicle test weight (lbs)
x	Distance (km)
δ	Mass correction factor
θ	Angle of the road grade
ρ	Density of air (1.2 kg/m3)

1 Introduction
This thesis is an exploration of the effects of driving style and vehicle performance on real-world fuel consumption. It is based on 1) the sensitivity of fuel consumption to driving style and 2) real-world driving styles, both of which related to and are affected by vehicle performance.

1.1 Motivation
This work is part of a larger effort by the MIT Sloan Automotive Laboratory to understand the potential for reducing light-duty vehicle (LDV) fuel use over both the near- and long-term. The need to reduce U.S. LDV fuel use has arisen from the need to reduce both our dependence on foreign petroleum and our greenhouse gas (GHG) emissions. Petroleum accounts for over 97 percent of LDV energy consumption, and over 60 percent of U.S. petroleum is imported [EIA, 2009]. Additionally, the petroleum consumption from U.S. light-duty vehicles creates almost 1.3 Gt of CO2 each year, accounting for close to 5 percent of global carbon dioxide (CO_2) emissions [IEA, 2009]. In addition, Bin and Dowlatabadi [2005] showed that individual behaviors account for roughly 40 percent of total U.S. CO_2 emissions.

There are a wide variety of options for reducing LDV fuel use and GHG emissions. These include switching to advanced technology vehicles, transitioning to low-carbon fuels, reducing vehicle miles traveled, and reducing vehicle size and weight. The potential reductions from many of these options and the dynamics affecting their potential have been explored by the Sloan Automotive Laboratory over the past few years and are described in "On the Road in 2035" [Bandivadekar et al., 2008]. This work focuses on reducing LDV fuel use through changes in driving style, specifically driving aggressiveness. Building from the dynamics of LDV fuel use described in "On the Road in 2035," understanding the effect of driving style on fuel consumption is important for:

- Addressing near-term fuel consumption of the current vehicle fleet,
- Understanding the fuel economy shortfall, and
- Exploring the role of vehicle performance in driving aggressiveness.

Address Near-term Fuel Consumption
One of the main barriers to achieving more dramatic reductions in U.S. light duty vehicle fuel use is the slow turnover rate of the entire light-duty vehicle fleet. As demonstrated in Figure 1, it takes 25 to 30 years for the entire LDV fleet to turnover. In addition, although there are several approaches and varying estimates of vehicle survival rates, all agree that vehicle lifetime has increased since the 1970s [Bandivadekar et al., 2008]. Because of this slow turnover, there is a roughly 10 year lag between reductions in new vehicle fuel consumption and reduction in fleet fuel use [Bandivadekar et al., 2008]. This lag limits the ability of new technologies to reduce near-term fuel use. Methods are needed to address the fuel consumption of both 1) conventional, naturally aspirated, spark-ignited internal combustion engine (SI-ICE) vehicles and 2) the current, existing vehicle fleet. Changing driving style is one of very few opportunities for achieving both of these. Limited previous research seems to indicate that typical drivers could reduce their fuel consumption by 10 percent by changing their driving style [Greene, 2008].

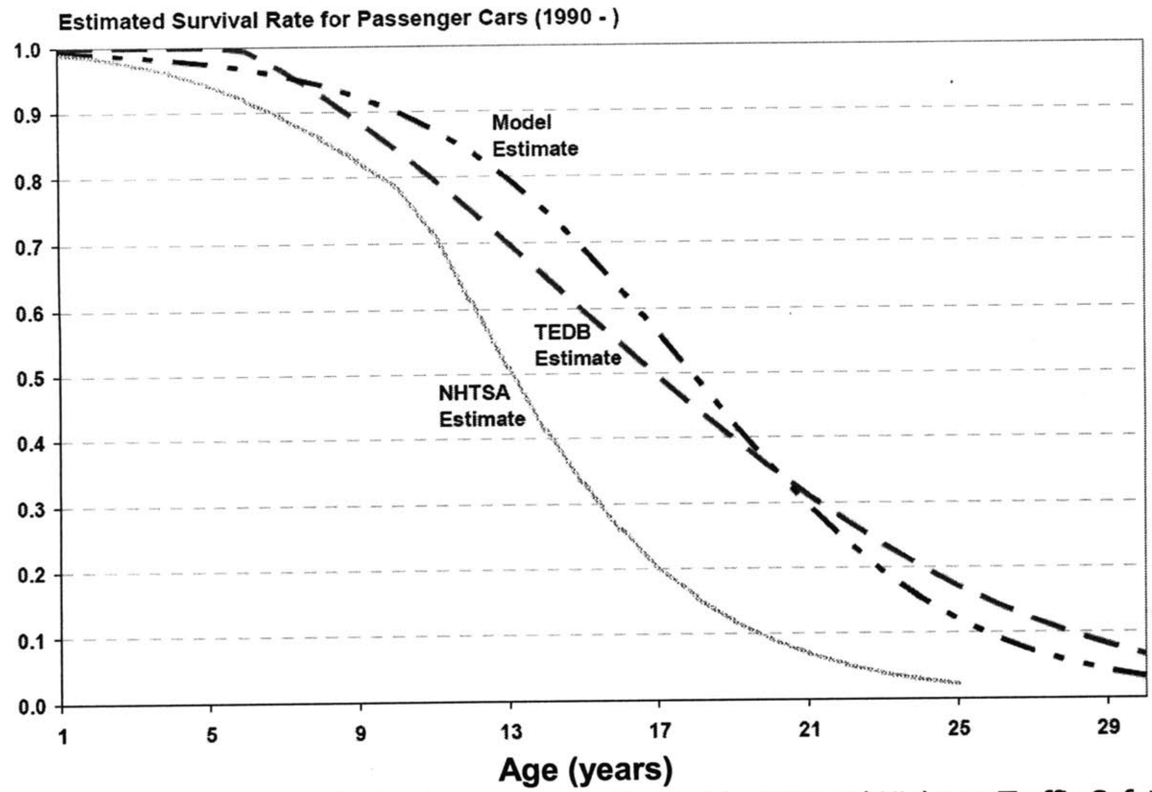

Figure 1: Vehicle survival rate by age as estimated by National Highway Traffic Safety Administration (NHTSA), the Transportation Energy Data Book (TEDB), and the MIT LDV fleet model; from [Bandivadekar et al., 2008]

Understanding the Fuel Economy Shortfall

The "on-road gap" or "fuel economy shortfall" is the difference between certified and on-road fuel consumption. This difference is due to a combination of factors, one of which is the aggressiveness of the driving style. Figure 2 shows estimates of total LDV fuel use for three levels of shortfall, expressed as percent degradation. The higher the degradation factor, the higher on-road fuel consumption is relative to certified or label values. As shown, fleet fuel use is quite sensitive to this value. This sensitivity to shortfall points to the high potential for changes in driving style to reduce fleet fuel use. In addition, currently, there is great uncertainty over the shortfall, making accurate fleet modeling difficult.

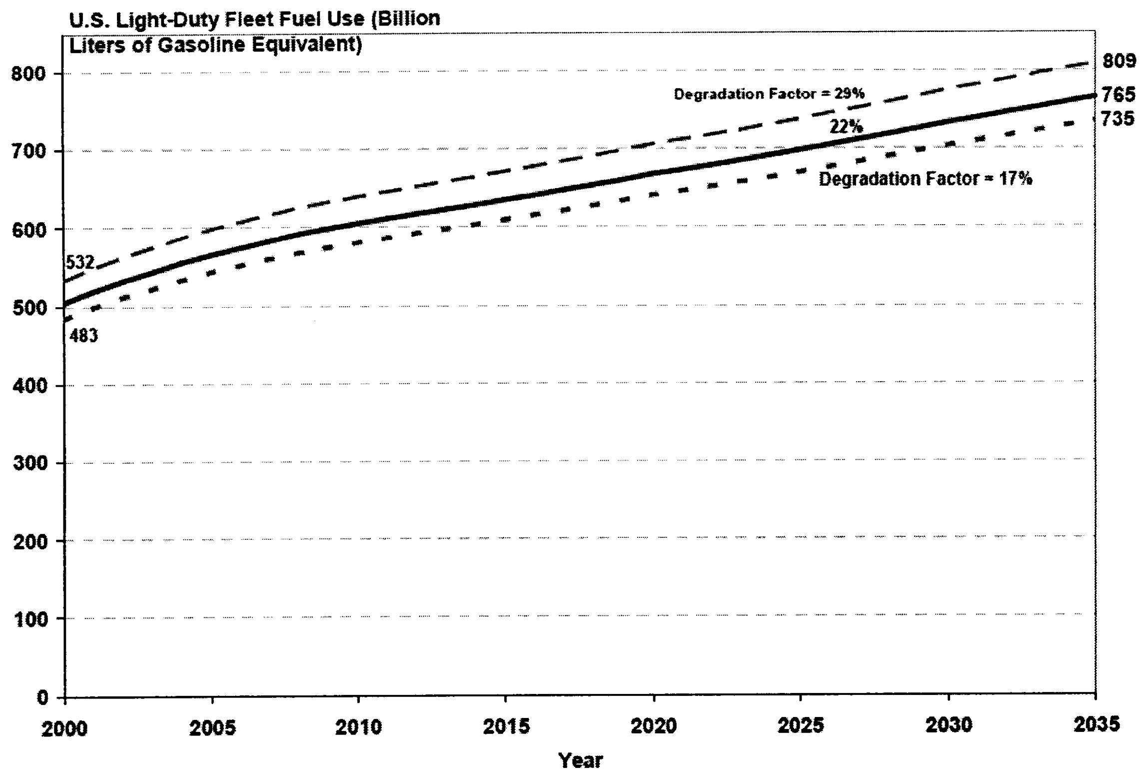

Figure 2: LDV fleet fuel use from 2000 to 2035 for varying levels of shortfall; from [Bandivadekar et al., 2008]

Exploring the Role of Vehicle Performance

As discussed in An and DeCicco [2007] and Bandivadekar et al. [2008], there is a tradeoff between vehicle performance and fuel consumption. Increases in vehicle efficiency can be used to 1) reduce certified fuel consumption or 2) increase vehicle horsepower, weight, or size. Increasing vehicle weight increases certification fuel consumption linearly. And, for a given vehicle weight, increasing engine horsepower (or power-to-weight ratio) increases fuel consumption. As shown in Figure 3, trends of increasing vehicle performance help explain why fuel consumption has remained relatively flat in the U.S. over the last 20 years despite increases in vehicle efficiency.

Additionally, other studies have shown that vehicle performance is tied to shortfall, a vehicle's sensitivity to aggressive driving, and the aggressiveness of driving. McNutt et al. [1982] and Mintz et al. [1993] showed that vehicles with higher fuel consumption have lower shortfall. Energy and Environmental Analysis, Inc [2001] showed that vehicles with higher power-to-weight ratios are less sensitive to changes in driving style. Brundell-Freji and Ericsson [2005] found that power-to-weight ratio had a fairly large impact on overall driving style.

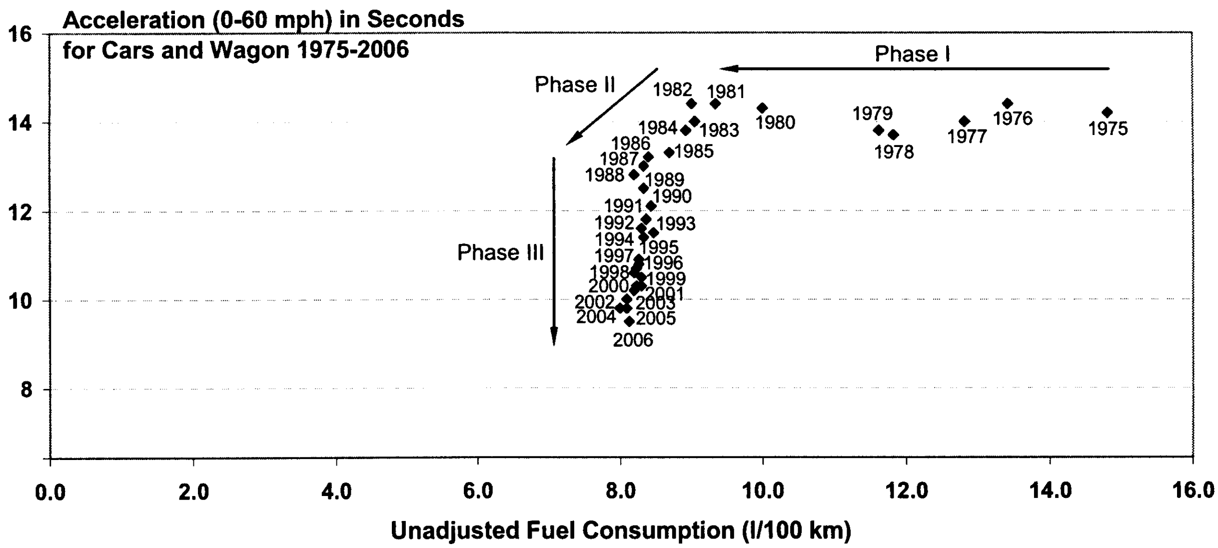

Figure 3: Average acceleration time versus unadjusted certified fuel consumption for new cars and wagons from 1975 to 2006; from [Bandivadekar et al., 2008]

1.2 Research Questions

This work seeks to explain, on a fundamental level, how specific driving behaviors impact the fuel consumption of our vehicles and to develop a metric for assessing driving aggressiveness based on fuel consumption. The central question it seeks to answer is: which behaviors, by the drivers of which vehicles, use the most fuel and which offer the greatest potential for fuel savings? In order to answer this question, two sets of sub-questions must first be answered: 1) those related to the technical relationship between driving style and fuel consumption and 2) those related to driving in the real world.

Driving Style and Fuel Consumption

It is not well understood, in a quantitative way, how specific driving behaviors impact vehicle fuel consumption or how sensitive these impacts are to vehicle design. The estimates currently available are based on very limited testing. Although the role of driving style has received increased media coverage in the last few years, there is no consistent or applicable source of this information. Therefore, the first part of this research seeks to answer:

- How does driving style affect the fuel consumption of a conventional, SI-ICE vehicle?
- Which specific driving behaviors cause the greatest increases in fuel economy?
- Can a metric be developed to characterize driving aggressiveness?
- How does vehicle performance affect the sensitivity of fuel consumption to driving style?

Real-World Driving

It is accepted by many that the shortfall between certified and on-road fuel consumption has increased in the U.S. over time. However, few estimates of current driving aggressiveness exist. In addition, most studies of on-road fuel economy find that smaller, higher fuel economy vehicles tend to have larger shortfall than larger, more powerful vehicles. It is not clear whether this is due to differences in driving style or in vehicle sensitivity to driving aggressiveness. The second part of this research seeks to answer:

- How do people drive today?
- Are more powerful vehicles driven with more "inefficient" driving styles?

1.3 Report Overview

Chapter 2 provides background information on many of the issues and topics related to driving style, vehicle performance, and fuel consumption. Chapter 3 describes the methodologies considered and those used in this work. A two-part approach is utilized, with one part aimed at answering each set of sub-questions:

1. Using vehicle simulations and vehicle dynamics to study the sensitivity of fuel consumption to driving aggressiveness and
2. Analyzing driving data to evaluate the aggressiveness of real-world driving styles

Chapter 4 defines vehicle and drive cycle dynamics. While somewhat tedious, Chapter 4 is important since these variables are used to explain and characterized driving aggressiveness. Chapter 5 investigates the results of extensive vehicle simulations. Simulation results for the case of steady-speed driving are examined in detail. Then, simulations of transient driving patterns support conclusions about the effect of velocities and accelerations on fuel consumption. Building from this understanding, Chapter 6 combines the simulation results and vehicle dynamics to define a method, a set of aggressiveness factors, for quantifying driving aggressiveness. Throughout these chapters, the role of vehicle performance in the relationship between driving style and fuel consumption is explored, but only to illustrate impacts.

Chapter 7 reviews two sets of real-world driving data to 1) demonstrate how the aggressiveness factor can be used, 2) estimate real-world aggressiveness, and 3) explore how vehicle characteristics, specifically power-to-weight ratio, affect driving aggressiveness. Based on the distribution of velocities and accelerations in the real-world data, and assumption about how those distributions might change, potential fuel savings are estimated.

Chapter 8 integrates the results of the individual chapters, summarizing the significant findings and providing tips for both individual drivers and policy-makers to save fuel though changes in driving style.

2 Context

Interest in the effect of driving style on fuel consumption has fluctuated over time among researchers, policy-makers, and the pubic. Most recently, the combination of high gasoline prices and new EPA fuel economy labels raised awareness about the potential for fuel savings. This chapter provides background on the issues of driving style, vehicle performance, and fuel consumption. These issues relate to a wide range of topics, such as fuel economy testing, drive cycle development, fuel economy labeling, the fuel economy shortfall, and eco-driving. Each of these areas is summarized. In addition, numerous methods have been used in the literature to describe drive cycles and driving aggressiveness and are reviewed here. But first, some common terms are defined.

2.1 Definitions

The terms driving, drive cycle, and driving behavior can be used to mean a variety of things. In addition, there is often confusion over the differences between fuel consumption, fuel economy, fuel use, and efficiency. For this work the following definitions are used for simplicity:

Driving Style – Driving style refers to the level of driving aggressiveness and includes the effects of the vehicle, driver, and driving environment. Driving style can be thought of as the accumulated velocities and accelerations used during a specific type or mode of driving.

Driving Behaviors – Driving behaviors are instantaneous velocities and/or accelerations.

Speed Trace – A speed trace time-series vehicle velocity data. Speed traces include both drive cycles and real-world driving patterns.

Drive Cycle – A drive cycle is a standard speed trace. Drive cycles are sometimes, but not always, based on real-world driving. They are generally used for either fuel consumption or emissions testing to provide a common test procedure. Additionally, when used for certification purposes, additional characteristics such as the temperature of the test are specified.

Driving Pattern – A driving pattern is an un-modified speed trace collected directly on the road and represents "real-world" driving.

Fuel Economy – Fuel economy, or mileage, is the relationship between distance traveled and the amount of fuel consumed for a specific vehicle and speed trace. Fuel economy is most commonly expressed as miles per gallon (MPG).

Certified Fuel Economy – Certified fuel economy is the fuel economy of a vehicle over a regulatory drive cycle or set of regulatory cycles, specifically the fuel economy value used by the EPA for labeling. The importance of certified fuel economy is simply that the drive cycle is the same for all vehicles.

Fuel Consumption – Fuel consumption is the inverse of fuel economy. It is the rate of consumption per unit distance and is usually expressed in units of liters per 100 km (L/100km) or gallons per mile (GPM).

Fuel use – Fuel use is the total fuel used (in liters or gallons) by a vehicle or fleet.

Efficiency – Efficiency is the ratio of power out to power in, expressed as a percentage. Like fuel use, efficiency conveys no information about the distance traveled.

2.2 Fuel Economy Testing

Fuel economy is tested and certified for both the Corporate Average Fuel Economy (CAFE) Standards and fuel economy labels based on controlled laboratory tests. The procedures for these tests are prescribed by federal law. The vehicle is placed on a chassis dynamometer with its drive wheels on rollers. A test driver then "drives" the vehicle over a prescribed, certification drive cycle. A drive cycle is a second-by-second speed trace developed specifically to represent a specific type of driving. In order to account for the energy required for aerodynamic drag and acceleration, the dynamometer adjusts the energy required to spin the rollers, depending on the velocity and acceleration of rotation. In addition to a prescribed speed trace, ambient conditions such as temperature and humidity are also prescribed, as well as, engine start condition (cold or warm) and air conditioning use. Table 1 summarizes the key characteristics of the five drive cycles used in the U.S. to certify fuel economy today, the FTP, HWFET, US06, SC03, and C-FTP. These drive cycles will be described in more detail below. Most fuel economy tests are performed and certified by the automakers themselves. The EPA then tests 10 to 15 percent of vehicles each year to confirm the results [EPA and DOE].

Table 1: Characteristics of U.S. certification drive cycles; adapted from [Davis et al., 2009]

Drive Cycle	FTP	HWFET	US06	SC03	C-FTP
Description	Urban/city	Free-flow traffic on highway	Aggressive driving on highway	AC on, hot ambient temp	City, cold ambient temp
Regulatory Use (2010)	CAFE & Label	CAFE & Label	Label	Label	Label
Data Collection Method	Instrumented vehicles / specific route	Chase-car / naturalistic driving	Instrumented vehicles / naturalistic	Instrumented vehicles / naturalistic	Instrumented vehicles / specific route
Year of Data Collection	1969	Early 1970s	1992	1992	1969
Top speed	90 kph (56 mph)	97 kph (60 mph)	129 kph (80 mph)	88 kph (54 mph)	90 kph (56 mph)
Avg. velocity	32 kph (20 mph)	77 kph (48 mph)	77 kph (48 mph)	35 kph (22 mph)	32 kph (20 mph)
Max. Accel.	1.48 m/s^2	1.43 m/s^2	3.78 m/s^2	2.28 m/s^2	1.48 m/s^2
Distance	17 miles (11 km)	16 miles (10 km)	13 miles (8 km)	5.8 miles (3.6 km)	18 miles (11 km)
Time (min)	31 min	12.5 min	10 min	9.9 min	31 min
Stops	23	None	4	5	23
Idling time	18 %	None	7 %	19 %	18 %
Engine start	Cold	Warm	Warm	Warm	Cold
Lab temp.	68-86 ° F	68-86 ° F	68-86 ° F	95 ° F	20 ° F
Air conditioning	Off	Off	Off	On	Off

2.3 U.S. Certification Drive Cycles

The drive cycles used to certify vehicle fuel economy in the U.S. today were developed to represent typical driving in a specific location and mode of driving. This section gives an overview of U.S. drive cycles and how they were developed. Two cycles are shown here; the remaining cycles are pictured in Appendix A. The next section describes how these drive cycles are used and adjusted for fuel economy labels and CAFE standards.

The first drive cycles were developed in the 1950s by the Los Angeles County Air Pollution Control District for emissions measurement of typical LA driving. At that time, researchers characterized real-world driving database on the proportion of time spent in specific engine speed-manifold pressure bins. These bins were used to define "modes" of driving. Based on a survey of 1956 driving, the 7-mode drive cycle, the first certification drive cycle, was developed. As the name suggests, it consisted of only 7 modes, or acceleration rates, weighted to represent typical driving. This cycle was used to test emissions in CA from 1966 to 1971 [Kruse and Huls, 1973]. ("Mode" drive cycles such as this are used today in Europe and Japan, these include the ECE, EUDC, NEDC, Japan 10-mode, Japan 15-mode, and Japan 10/15-mode cycles shown in Appendix A.)

In 1969, work began on a more realistic drive cycle, specifically to represent "typical" morning (home-to-work) driving in LA. A specific 12 mile route, called the LA 4 road route, beginning and ending at the California emissions laboratory was selected as the basis of this new drive cycle. In 1969, six different EPA personnel drove the route. From this data set, a speed trace was selected and shortened to represent the average commute length in LA at that time. Then, all accelerations and decelerations were cut back to 3.3 mph/s (or 1.5 m/s^2), the maximum design rate of a dynamometer at that time. This shortened and modified drive cycle forms the Urban Dynamometer Driving Schedule (UDDS), shown in Figure 4, also referred to as the LA4-S3, the LA4, or the FTP 72. It covers 7.5 miles with an average speed of 19.6 mph (31.5 kph) [Austin et al., 1993]. The initial 505 seconds of this cycle is repeated and added to the end of the UDDS following a 10 minute hot soak to form the Federal Test Procedure (FTP), also called the FTP 75 [Kruse and Huls, 1973].

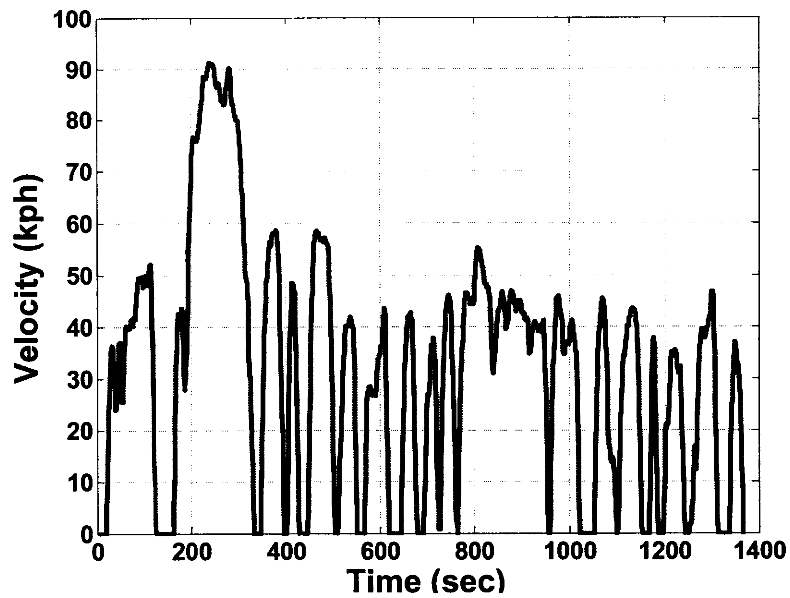

Figure 4: The UDDS drive cycle

In the 1970s, the EPA began to publish city fuel economy numbers based on the FTP cycle. The need for a highway cycle became evident. Unlike with the development of the LA4, the highway cycle was generated from over 1,050 miles of vehicle speed data. This data was collected on non-urban roads in Michigan, Ohio, and Indiana (areas with a strictly-enforced 55 mph speed limit) using a "chase car" approach, and then processed into a representative 11 mile cycle. As with the FTP, accelerations and decelerations were limited to 3.3 mph/s. The resulting drive cycle is the Highway Fuel Economy Test (HWFET).

In 1992 the EPA completed a new study of real-world driving, the "3-Cities" study based on driving in Baltimore, Spokane, and the South Coast Air Basin (SCAB) around LA, as well as, in Atlanta. A combination of instrumented vehicle and chase cars were used. The driving observed was more aggressive that the existing FTP and HWFET drive cycles. The results were used to develop the B92 (Baltimore), S92 (Spokane), and LA92 (Los Angeles) drive cycles, as well as, the ARB02 (California Air Resources Board drive cycle number 2) and REP05 (representative drive cycle number 5). The LA92 drive cycle, also often referred to as the Unified Cycle (UC), is shown in Figure 5. By this time, dynamometer technology had improved and higher acceleration rates were possible. These new drive cycles were not limited to acceleration rates of 1.46 m/s^2 and lower.

Recognizing that the FTP and HWFET were no longer representative of on-road driving, in 1990s, the EPA developed supplemental drive cycles based on data collected in the 1990s. These are the US06, SC03, and C-FTP (or cold- FTP). The US06 represents aggressive highway driving, while the SC03 represents city driving with the air conditioner on. The C-FTP is the FTP drive cycle, but at low ambient temperature. These cycles were recently incorporated into the EPA's fuel economy certification procedure, resulting in the "5-cycle" city and highway fuel economy numbers described below. The 5-cycles are the FTP, HWFET, US06, SC03, and C-FTP. There are only four speed traces since the C-FTP speed trace is the same as the FTP.

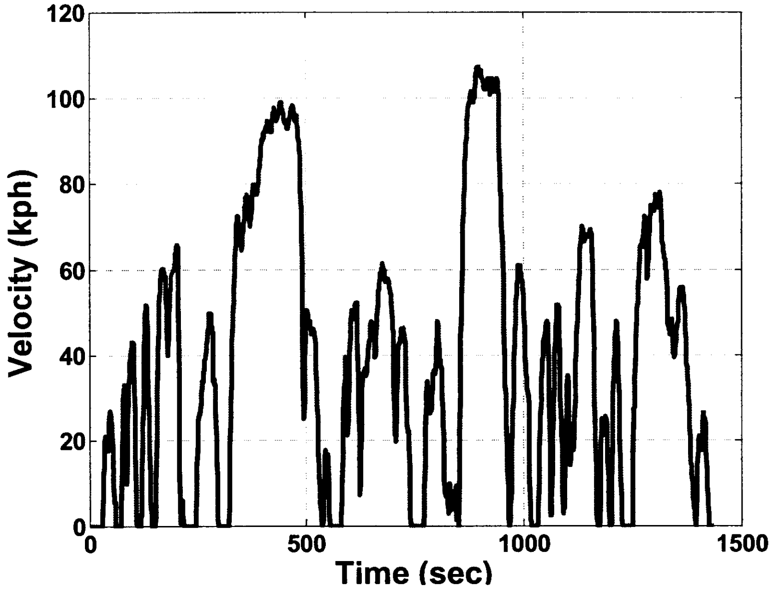

Figure 5: The LA92 drive cycle

2.4 EPA Fuel Economy Labels

Although the EPA began publishing city fuel economy numbers in the early 1970s, the official fuel economy labeling program began in 1975. These original fuel economy labels used fuel economy over the FTP and HWFET drive cycles to represent city and highway driving, respectively. Combined fuel economy was calculated by harmonically averaging the city and highway fuel economies with weightings of 55 percent and 45 percent, respectively, through Equation 1. This combined fuel economy is the value used in calculating automakers Corporate Average Fuel Economy (CAFE). These three fuel economy numbers are "unadjusted" since no adjustment factors are applied. Because the tests are standard and repeatable, fuel economy labels provide a way to compare and contrast fuel economy across vehicles.

$$EPA\ Combined\ MPG\left[1972\text{ - }1984\right]=\frac{1}{\left(\frac{0.55}{\left[FTP\ MPG\right]}+\frac{0.45}{\left[HWFET\ MPG\right]}\right)} \qquad (1)$$

Almost immediately with the creation of the fuel economy labels, consumers began to notice on-road fuel economy was significantly lower than that on the label. Consequentially, EPA began a program to revise the label numbers. Instead of developing or using new drive cycles, adjustment factors were developed. Based on average miles driven, the fraction of city and highway driving, and actual test results for a variety of vehicles, Hellman and Murrell [1984] estimated an adjustment factor of 0.9 for city driving and 0.78 for highway driving. Beginning in 1985, these adjustment factors were applied to the FTP and HWFET fuel economy values to generate "adjusted" fuel economy numbers for the EPA labels (but not CAFE). The resulting combined fuel economy is defined in Equation 2. Following these revisions, the test procedures for fuel economy labels remained the same for over 20 years, until 2008.

$$EPA\ Combined\ MPG\left[1985\text{ - }2007\right]=\frac{1}{\left(\frac{0.55}{0.9*\left[FTP\ MPG\right]}+\frac{0.45}{0.78*\left[HWFET\ MPG\right]}\right)} \quad (2)$$

In 2005 and 2006, the EPA preformed an extensive review of the fuel economy labels and revised the test procedure and calculation yet again. The new, "5-cycle" fuel economy values are calculated though a combination and specific weighing of the "city" and "highway" portions of the 5 drive cycles. For 2003–2006 model year vehicles, the new highway fuel economy estimates are, on average, 8 percent lower, and city fuel economy estimates are, on average, 12 percent lower [EPA, 2006]. An approximation of the 5-cycle fuel economy values can be calculated directly from the "unadjusted" FTP and HWFET fuel economy values. The EPA refers to these questions as the "MPG-approach" for calculating new fuel economy label values. They are provided in Equation 3 and Equation 4 [EPA, 2006]:

$$EPA\ Highway\ MPG\left[2008+\right]=\frac{1}{\left(0.001376+\frac{1.3466}{\left[HWFET\ MPG\right]}\right)} \quad (3)$$

$$EPA\ City\ MPG\left[2008+\right]=\frac{1}{\left(0.003259+\frac{1.1805}{\left[FTP\ MPG\right]}\right)} \quad (4)$$

Under the new fuel economy labeling method, a 43/57 city/highway weighting is used to generate the combined fuel economy value:

$$EPA\ Combined\ MPG\left[2008+\right]=\frac{1}{\left(\frac{0.43}{\left[5\text{ - }cycle\ city\ MPG\right]}+\frac{0.57}{\left[5\text{ - }cycle\ highway\ MPG\right]}\right)} \quad (5)$$

Figure 6 and Figure 7 show the changes in the city and highway fuel economy labels.

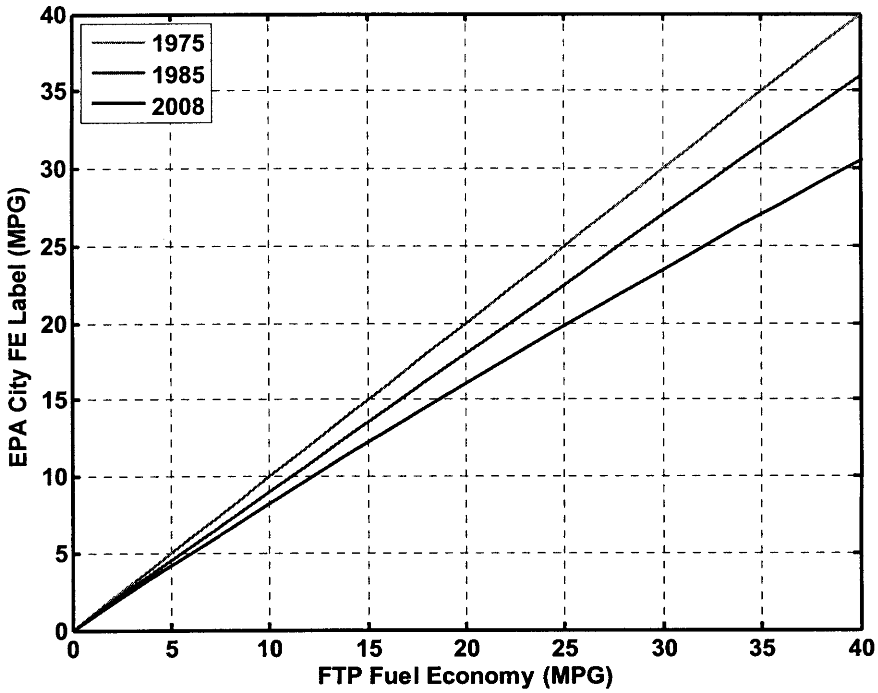

Figure 6: City fuel economy label values versus unadjusted FTP fuel economy

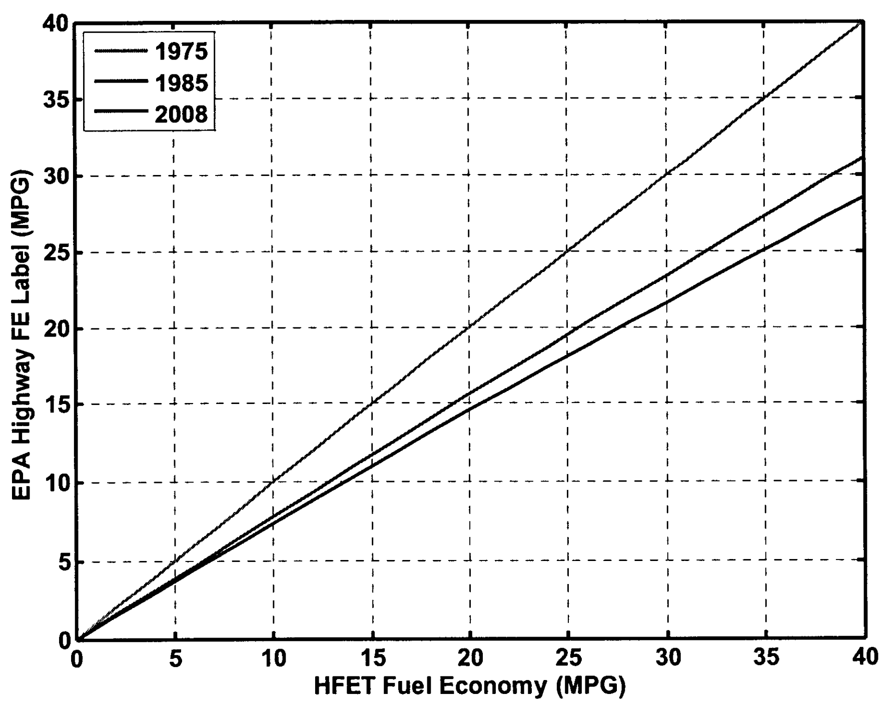

Figure 7: Highway fuel economy label values versus unadjusted HWEFT fuel economy

2.5 Fuel Economy Shortfall

As reflected in the adjustments to the EPA's fuel economy labels over time, there is a recognized fuel economy "shortfall" or "on-road gap" between EPA certified and on-road fuel economy. Understanding this shortfall is particularly important for modeling and assessing total LDV petroleum consumption and emissions. Fleet models, such as the one developed at MIT [Bandivadekar, 2008] or by the International Energy Agency (IEA) [Fulton and Eads, 2004], generally apply "degradation" or "adjustment" factors to account for shortfall. As shown in Chapter 1, fleet fuel use is highly dependent upon these adjustment factors. For this work, shortfall will be expressed, like an adjustment factor, as a ratio of certified- to on-road fuel economy, a "Gallons per Mile Ratio" or GPMR. Shortfall can also be expressed as a percent difference between either 1) certified and on-road fuel economy or 2) certified and on-road fuel consumption. A GPMR of 0.75 means that the vehicle achieves 25 percent lower fuel economy and 33 percent higher fuel consumption. The conversions to percent increase in fuel consumption and fuel economy are given by Equation 6 and Equation 7.

$$\textit{Percent increase in fuel consumption} = \frac{100}{\left(\left(\frac{1}{GPMR}\right)-1\right)} \tag{6}$$

$$\textit{Percent decrease in fuel economy} = 100*(1-GPMR) \tag{7}$$

The magnitude of the increase in fuel consumption due to shortfall is thus dependent on absolute fuel consumption, as shown in Figure 8.

Estimates of shortfall have changed over time, as summarized in Table 2, but are generally on the order of 0.75 to 0.85 (a 25 to 15 percent increase in fuel consumption). They tend to distinguish between either car and light truck shortfall or city and highway shortfall.

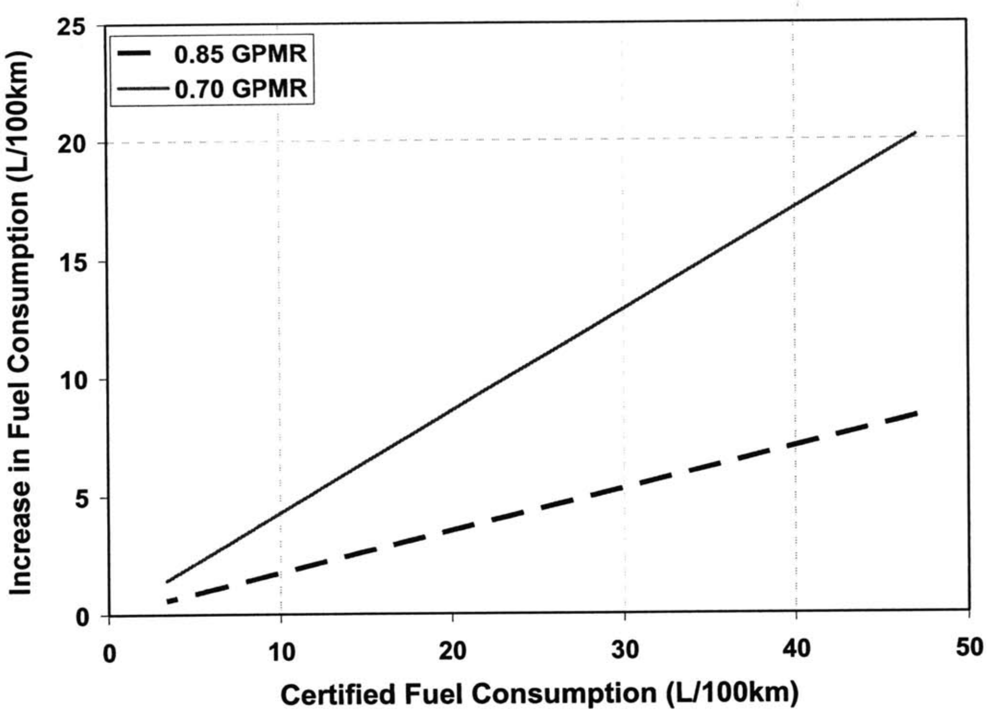

Figure 8: Magnitude of increase in fuel consumption versus certified fuel consumption for two levels of shortfall

Table 2: Estimates of shortfall, by car or light truck and by city and highway driving

Source	Survey Data	Cars	Light Trucks
Hellman and Murrell [1982]		0.90	
McNutt et al. [1982]		0.81 - 0.85	
Mintz, Vyas, and Conley [1993]	1985 Residential Transportation Energy Consumption Survey	0.81	0.80
Consumer Reports [2005]	Average of all vehicles tested	0.70	
Duleep [2008]		0.80 - 0.75	
		City	**Highway**
Hellman and Murrell [1984]	GM - Survey by MY 1980 / 1981	0.87 / 0.87	0.79 / 0.77
	Chrysler - Survey by MY 1981 / 1982	0.87 / 0.85	0.75 / 0.74
	Ford - Survey by MY 1979 / 1980 / 1981	0.89 / 0.84 / 0.87	0.83 / 0.82 / 0.82

Sources of Shortfall

Sources of this shortfall include everything from vehicle-level variation at the manufacturing plant to environmental characteristics and long-term vehicle maintenance. Nevertheless, the primary sources of shortfall are differences between the EPA procedures (summarized in Table 1) and actual driving conditions. These sources can be grouped into differences in:

- Ambient conditions, such as temperature, humidity, and precipitation;
- Vehicle conditions, such as cargo weight, maintenance, tire pressure, accessory loads, use of "off-cycle' devices, and aerodynamic changes from a roof rack or open windows; and
- Speed traces due to traffic, speed limits, and driver.

This research focuses on the shortfall due to differences in speed traces. But even this source of shortfall comes from a combination of two factors:

1. The sensitivity of the vehicle to changes in driving style and
2. The difference in driving style between certification drive cycles and real-world driving.

This theme will emerge throughout this work as we distinguish between these two factors. It is thus important to keep track of how fuel consumption, the sensitivity of fuel consumption to changes in driving style, and shortfall are reported: relative to a standard drive cycle, randomly selected drive cycles, or real-world driving.

Even for certification drive cycles, test-to-test variability in the way the cycles are driven can cause up to a 3 percent difference in fuel economy [Andrews, Berger, and Smith, 2006]. This is because, for EPA certification purposes, the vehicle must follow the prescribed drive cycle within 2 mph every second. This 2 mph gap leaves significant room for both more and less aggressive driving.

Smaller sources of shortfall include "administrative variance" and "hardware variance." Administrative variance results when an administrative decision is made to change some small part of a vehicle between when the EPA certification tests are completed and when the vehicle reaches the showroom. Hardware variance is due to small differences in vehicles that occur during manufacturing. Even in 1982, both of these were essentially negligible: Hellman and Murrell [1982] observed a 0.999 GMPR shortfall due to "administrative variance" and a 0.985 GMPR shortfall due to "hardware variance.

Variation in Shortfall by Vehicle Technology

Even the earliest estimates of shortfall demonstrated a clear variation across different vehicles. In Hooker's 1985 shortfall study, the single most striking result was the car-to-car variation [Energy and Environmental Analysis, Inc, 2001]. Over time, the vehicle factors that affect shortfall have become better known and are summarized in Table 3. As shown in a number of studies and real-world fuel economy assessments, high fuel economy vehicle tend to have larger shortfall. Most of these vehicles are either high-technology vehicles, as in the case of hybrids, or sacrifice some performance for higher fuel economy. The higher shortfall these vehicles exhibit could be due to more aggressive driving, higher sensitivity to aggressive driving, a higher percentage of low speed driving, or other factors not related to driving style.

Table 3: Summary of the literature on the relative shortfall of various vehicle characteristics

Characteristic	Has Higher Shortfall	Compared to
Fuel Economy[+#]	High certified fuel economy	Lower certified fuel economy
Drive[+#]	Rear wheel drive	Front wheel drive
Transmission[+#]	Automatic	Manual
Injection[#]	Carbureted	Fuel Injection
Fuel/Combustion Type[+^]	Gasoline	Diesel
Vehicle Class[+*]	Trucks	Cars
Vehicle Size[*]	Smaller	Larger
Vehicle Age[*]	Older	Younger
Advanced powertrain (city driving)[**]	Hybrid electric vehicles	Conventional vehicles
Origin (Car)[*]	Domestic	Import
Origin (Truck)[*]	Import	Domestic

Sources: [*][Mintz et al., 1993], [+][McNutt et al.., 1982],[^][Abuelsamid, 2009], and [#][Hellman and Murrell, 1982], [**][Sharer et al.., 2007]

2.6 Eco-driving

Eco-driving is a way of driving that uses less fuel. It involves following a set of techniques such as upshifting to avoid engine speeds over 2,500 rpm, maintaining steady vehicle speed, anticipating traffic, accelerating and decelerating smoothly, and avoiding long idles. Although most eco-driving techniques include lower highway speed, it is most common for city or urban driving, where fuel savings can be achieved without lower average speed or longer travel times. There are wide ranging estimates of the fuel that drivers can save by employing these and other, related techniques for saving fuel.

Table 4 summarizes the fuel savings projected by some of these studies. Additional estimates are summarized by ITF [2007]. In general, over the long term, a 5 to 10 percent reduction in fuel consumption seems feasible through eco-driving. However, the percentage of fuel that can be saved reflects a combination of 1) people's willingness to drive differently and 2) the sensitivity of the specific vehicle to changes in driving aggressiveness.

Table 4: Summary of Potential Fuel Savings Identified in the Eco-driving Literature

Citation	Study Type and Size	Short-term	Long-term
Quality Alliance Eco-Drive [2004]			11.7 %
	Driving instructors and experts in Switzerland		12% (8 months) 21% (17 months)
	Eco-Drive course		12%
	simulator course	15%	17%
	simulator driving		25% (max)
	Eco-training as part of the new driver training		0%
Henning [2008] (Ford of Europe)	German-wide (1998-2000); 300 participants	25% (average)	15% (max) 10% (average)
	Leipzig Motor Show; (74 people trained)	26.1%	
	Frankfurt Motor Show; (765 people trained)	20.65%	
Ford Motor Company [2008]	Intense 4-day class	24% (average)	
Onoda [2009]	Summary of EcoDrive Program in Europe	5 to 15%	5% (no feedback) 10% (w/ feedback)
Vermeulen [2006]	Study by TNO: 24 drivers over predefined route		7% (gasoline) 8 to 10% (diesel)
Taniguchi [2007]	Study of eco-driving training	20%	
Beusen and Denys [2008]	VITO study of 8 drivers following training		-1.7% to 7.3%
Beusen et al. [2009]	VITO study of 10 drivers following training	12 to -3% 5.8% (average) (4 months)	
Barth and Boriboonsomsin [2009]	Simulations with limited real-world experiments	10 to 20%	
Bragg [2009] (FuelClinic.com)	620 FuelClinic.com users following driving tips	5.23%	
Saynor [2008] (Ford Motor Company)	Driving trials by Ford Motor Company and Energy Savings Trust: total of 494 drivers	17 to 25%	
Mele [2008]		35% (average)	
WBSD [2008]	Fuel economy training courses offered by Volkswagen and Naturschutzbund Deutschland	13% (average) 25% (max)	

2.7 The Role of Vehicle Performance

Vehicle performance relates to our discussion of driving and fuel consumption in two ways. First, there is a recognized tradeoff between certified fuel consumption and performance, as discussed in the introduction. And second, vehicles with higher performance are capable of higher velocities and accelerations (more aggressive driving).

There is an inverse power relationship between a vehicle's power-to-weight ratio and its 0-60 acceleration time, represented by Equation 8:

$$t_{0-60mph} = F * (HP / WT)^{-f} \tag{8}$$

where, $t_{0\text{-}60mph}$ is the estimated 0-to-60 mph time of the vehicle in seconds, *HP* is the rated power of the engine in horsepower, *WT* is the vehicle inertia weight (curb weight plus 300 pounds) in pounds, and *F* and *f* are constants. For MY1975 - 1976 vehicles with automatic transmissions; Malliaris, Hsai, and Gould [1976] found *F* to be 0.892 and *f* to be 0.805. For vehicles with manual transmissions of the same model years, they found *F* and *f* to be 0.967 and 0.775, respectively

An analysis of MY2001 - 2009 vehicles, using data from Motor Trend, Truck Trend, Edmunds, and Autostats, updates the trend, as shown in Figure 9. The relationship between power-to-weight ratio and 0-60 mph acceleration time is still tight and exponential. However, there is a noticeable shift in the relationship. In particular, for power-to-weight ratios between 0.03 and 0.20 hp/lb, the 0-60 mph times observed today are lower than those observed during the MY1975 – 1976 study. As discussed by [Edmunds, 2008], there are many factors involved in testing 0-60 mph times which could account for some of this shift. This would need to be explored in more detail; however, these factors are not likely account for the entire shift.

A number of transitions in our vehicle technology between 1975 and today could also explain the shift in the relationship between 0-60 mph time and power-to-weight ratio. Specifically, engines are more powerful for a given engine size (expressed in cubic inches of displacement or CID) and more valves per cylinder. The carbureted engine has been replaced by port-fuel injection systems. For MY2009, nearly 80 percent of light duty vehicles had multi-valve systems, 65 percent employed variable valve timing, and 55 percent utilized front-wheel drive, versus 5 percent in 1975. The percentage of automatic transmissions has increased, and continuously variable transmissions have been introduced, accounting for 8 percent of LDVs in MY2009 [EPA, 2009].

Table 5 summarizes major changes in vehicle technology since 1975. Regardless of what trends explain the shift, the main point remains that vehicles with higher power-to-weight ratios are capable of achieving much higher top speeds and accelerations.

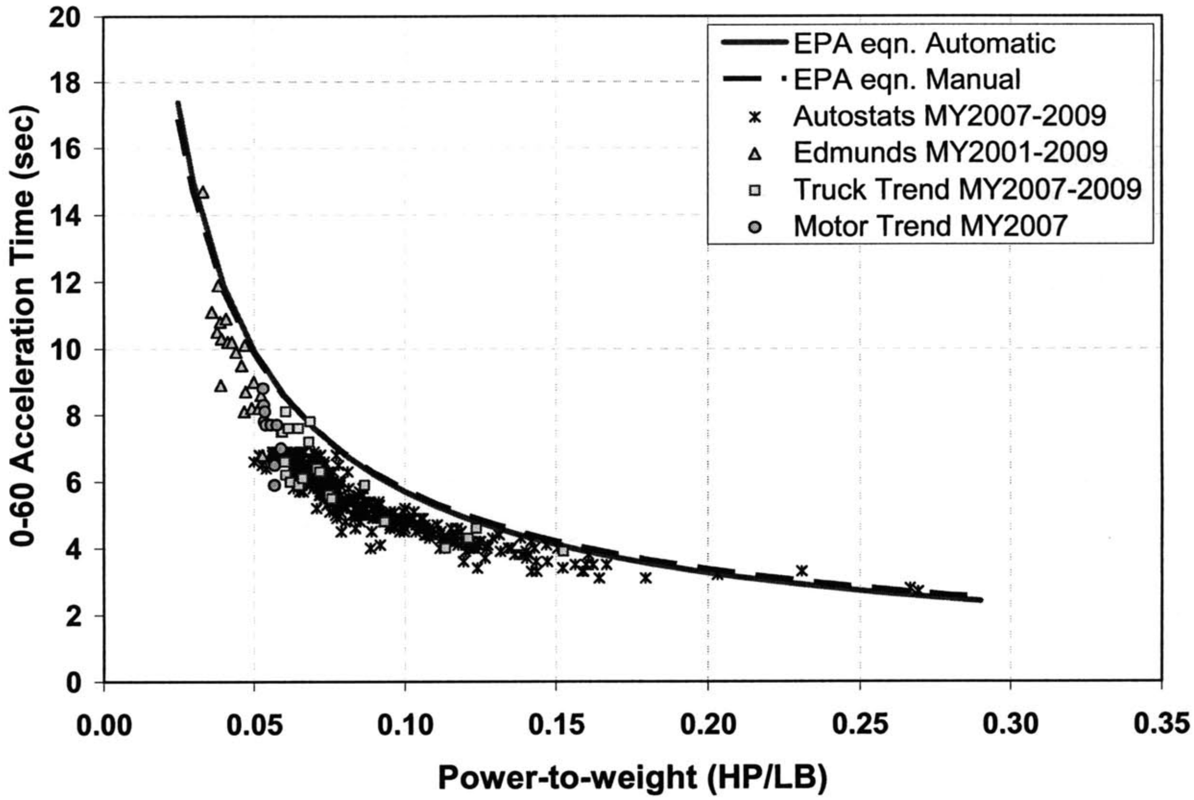

Figure 9: 0-60 mph acceleration time versus power-to-weight ratio based on the EPA equations identified by Malliaris, Hsai, and Gould [1976] and a survey of online vehicles from Edmunds [www.edmunds.com], Motor Trend [www.motortrend.com], Truck Trend [www.trucktrend.com], and AutoStats [www.performancecarnews.com].

Table 5: Characteristics of Light Duty Vehicles; from [EPA, 2009]

	1975	1987	1998	2009
Adjusted Fuel Economy (mpg)	13.1	22.0	20.1	21.1
Weight (lbs.)	4060	3220	3744	4108
Horsepower	137	118	171	225
Percent Truck Sales	19%	28%	45%	49%
Percent Front-Wheel Drive	5%	58%	56%	55%
Percent Four-Wheel Drive	3%	10%	20%	27%
Percent Multi-Valve Engine	-	-	40%	79%
Percent Variable Valve Timing	-	-	-	65%
Percent Cylinder Deactivation	-	-	-	9%
Gasoline-Direct Injection	-	-	-	3.5%
Percent Turbocharger	-	-	1.4%	3.1%
Percent Manual Trans	23%	29%	13%	6%
Percent Continuously Variable Trans	-	-	-	8%
Percent Hybrid	-	-	-	1.8%
Percent Diesel	0.2%	0.2%	0.1%	0.5%

2.8 Describing Driving Patterns and Drive Cycles

A key part of this work involves developing a set of metrics that can be used to quantify the aggressiveness of driving patterns and cycles. So it is useful to review the methods currently used to do this. There is no simple approach for characterizing driving style or aggressiveness.

Velocity and Acceleration Metrics

One common method for demonstrating the difference in aggressiveness between various drive cycles and with real-world driving is to simply list the characteristics of the drive cycles or patterns. Some of the more common variables to do this are summarized in Table 6.

Table 6: Common Values used to Describe Drive Cycles

Velocity-related	Acceleration-related	Stop-related	Velocity and Acceleration-related	Energy- and Power approximations
Average velocity	Average Positive Acceleration	Percent of time vehicle is stopped	Relative Positive Acceleration (RPA), relative to Time	Positive Kinetic Energy per unit distance (PKE)
Std. dev. of velocity	Std. dev. of Positive Acceleration	Average stops per distance	Relative Positive Acceleration (RPA), relative to distance	Specific Power (power per unit mass)
	Percent of time acceleration exceeds some value		Average Jerk (velocity times acceleration)	
	Average Deceleration			
	Std. dev. of Deceleration			

Fuel Consumption-based Approaches

There are a variety of ways that fuel consumption can be incorporated to characterize driving style. For example, the "eco-ratio" was defined by a Swiss eco-driving organization to evaluate changes in driving style before and after driver training. The eco-ratio is simply the average speed divided by fuel consumption [Quality Alliance Eco-Drive, 2004]; however, fuel flow or fuel consumption information is required.

Percentage of Driving Outside Standard Cycle

Another very common approach is to determine the percentage of a driving pattern or driving data that falls outside the range of a specific drive cycle, most often the FTP or HWFET. For example, the B92 database was evaluated by explaining that 18 percent of it fell outside of the FTP [EPA, 1993]. Often, the maximum acceleration and speeds of a collection of driving patterns or of a particularly drive cycle are plotted along with the FTP or HWFET cycle to demonstrate these differences graphically. Figure 10 shows the outer bounds of the FTP and HWFET (solid red line), along with the maximum accelerations and velocities in the 90s cycles (the US06, LA92, ARB02, and REP05 drive cycles) (slashed green line). As shown in Figure 10, the 90s cycles include much higher accelerations and decelerations than the original EPA city and highway cycles.

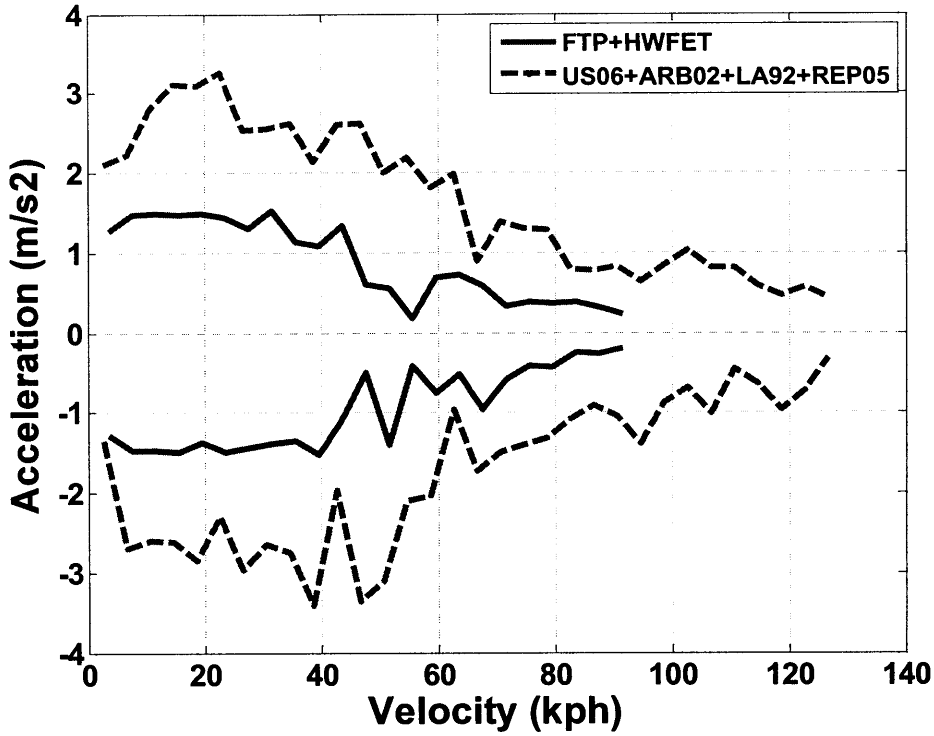

Figure 10: Maximum velocities and accelerations of the original EPA city (FTP) and highway (HWFET) drive cycles and the more aggressive drive cycles developed in the 90s (the US06, ARB02, LA92, and REP05).

Vehicle-specific Power

Vehicle specific power (VSP) is used to characterize driving for a specific vehicle and is the instantaneous tractive power per unit vehicle mass. As shown in Figure 11, VSP can be positive even when acceleration is negative due to the contribution from vehicle speed. For example, the MY2002 Ford Focus requires over 45 W/kg to maintain speed at 160 kph (99 mph). Most often, VSP is binned, and the time in each bin is used to estimate emissions and fuel consumption. This approach is particularly common for estimating and modeling pollutant emissions since it is often directly specified in emissions certification drive cycles [Jimenez-Palacios, 1999]. In addition, the EPA emissions models PERE (Physical Emission Rate Estimator) [Nam, 2004] and MOVES (MOtor Vehicle Emission Simulator) [Koupal et al., 2003] rely on the VSP method. However, the VSP approach over-predicts emissions at low average speeds and under-predicts emissions at higher average speeds.

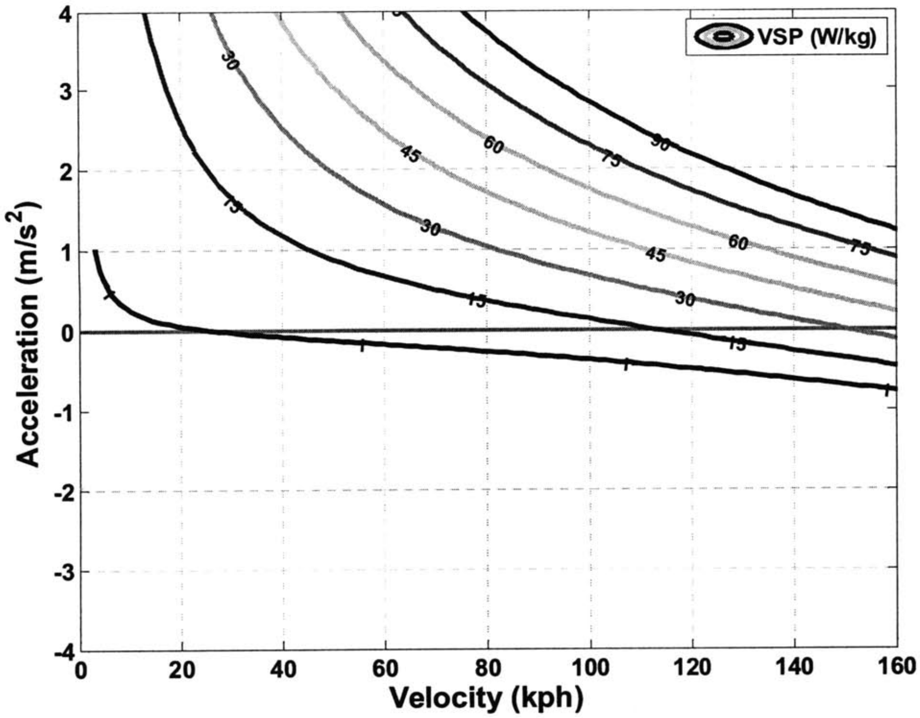

Figure 11: Vehicle-specific power for a Ford Focus.

3 Methodology

This chapter reviews the range of methodologies applied in the literature to characterize real-world driving and the effect of driving style on fuel consumption. It then describes, in detail, the methodologies used in this work which rely on vehicle simulations and naturalistic driving data.

3.1 Methodologies from the Literature

A wide range of researchers and professionals have studied both driving behavior and the effect of driving style on fuel consumption. Driving studies have generally been for the purpose of evaluating – and then modeling – congestion, traffic psychology, traffic safety, accidents, transit efficiency, mobile source emissions, and fuel consumption. A separate set of surveys and tests have sought to address fuel economy impacts. The primary methodologies from these two fields are: surveys, naturalistic driving studies, driving trials, driving simulators, portable emission measurement, and – in the case of fuel economy sensitivity – comparison across standard drive cycles.

Polls and Surveys

Traditionally, surveys and polls have been the prime sources of driving behavior information. The largest of these is the National Household Travel Survey (NHTS). This survey is sponsored by the Federal Highway Administration (FHWA). The most recent NHTS was completed in 2008 (although the data is still being processed and won't be released until early 2010). Some 155,000 households were interviewed in total. Polls, surveys, and diaries can also be used to monitor real-world fuel economy and on-road gap. These have primarily been preformed by the automotive industry and have historically been of limited size or population. The largest national consumption survey was the Residential Transportation Energy Consumption Survey (RTECS). This survey was completed every three years between 1983 and 1994. After 1994, EIA worked with DOT to include more energy-related questions into the NHTS. However, while polls and surveys are good for overall driving trends, they do not provide enough detail about the driving patterns to be of use for this work.

Naturalistic Driving Studies

Recently, naturalistic driving studies have also been used to provide study how drivers respond to circumstances and events under real-world driving conditions. These studies log normal, everyday trips from a large number of drivers with no instructions or intrusions. They rely primarily on instrumented vehicles, increasingly with GPS, and are sometimes combined with surveys to provide additional information about the drivers. Naturalistic driving studies have been aimed at answering questions related to: human factors, both within the vehicle and related to the highway system, road design, and traffic management among other things.

There are both pros and cons associated with using naturalistic driving data. The data is truly real-world in the sense that drivers are driving their own vehicles during their normal daily driving. However, because of this, there are many factors that change, not just vehicle and driver, but traffic conditions, time of day, weather, etc. Because so many of these other factors impact real-world fuel consumption, naturalistic driving is not appropriate to study the impact that driving has on fuel consumption. However, naturalistic driving studies are ideal to help assess the range of driving styles used on the road today, with some qualifiers and limitations.

Portable Emission Measurement

Portable emission measurement systems (PEMS) are used to provide real-world information, not of driving, but of emissions. These systems were introduced in the late 1990s to estimate pollutant emissions in non-attainment areas. These pollutants include hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides (NO_x), and sulfur oxides (SO_x). However, PEMS also measure carbon dioxide emissions, from which fuel consumption can be derived.

Driving Trials

Instead of recording normal, everyday trips, driving trials attempt to control some variables. Generally, they use either a specific real-world route and time of day or a controlled test track. These trials also tend to use instrumented vehicles driven by a limited number of drivers. When focused on driving behavior, no instructions are given to the drivers about how to drive. But driving trials can also be used to assess the effect of specific actions or devices on driving or fuel consumption. For such studies, each participant drives a set route at least twice, once before (or without) and once after (or with) the training (or device).

Although driving trials attempt to control many of the factors affecting fuel economy, given the high sensitivity of fuel consumption to even variation about the standard drive cycles, it is impossible to precisely account for all of these factors. In addition, by nature, driving trials can be expensive, and they provide only limited amounts of data, instead of the large magnitudes available from naturalistic driving studies.

Dynamometer Testing Across Drive Cycles

On common method for assessing the effect of driving style on fuel use is to compare the fuel consumption of vehicles across drive cycles that represent different levels of aggressiveness. This is the approach used by An and Barth [1998] to assess the sensitivity of hybrid-electric vehicle fuel economy to changes in driving style. A very similar approach was used to generate the statements about aggressive driving that appear on the EPA's fueleconomy.gov website (www.fueleconomy.gov). Energy and Environmental Analysis, Inc [2001] used the LA92 and US06 drive cycles to represent aggressive highway and city driving, and then compared fuel consumption over these cycles to fuel consumption on the FTP and HWFET cycles. The study concluded that, on average, there is a 33 percent difference in fuel economy between the US06 and HWFET drive cycles and a 5 percent difference between the FTP and LA92 drive cycles [Energy and Environmental Analysis, Inc. 2001].

Various levels of driving aggressiveness are also often represented by "multiplier drive cycles," in which standard or existing drive cycles are scaled by multiplying the speed traces by, for example, 1.2, 1.4, and 1.6. Figure 12 shows the HWFET with two such multiplier cycles. This approach alters the velocities, accelerations, and distances of the drive cycle. As one example, this was the approach was used by Sharer, Leydier, and Rousseau [2007] assess the impact of drive cycle aggressiveness on HEV fuel economy.

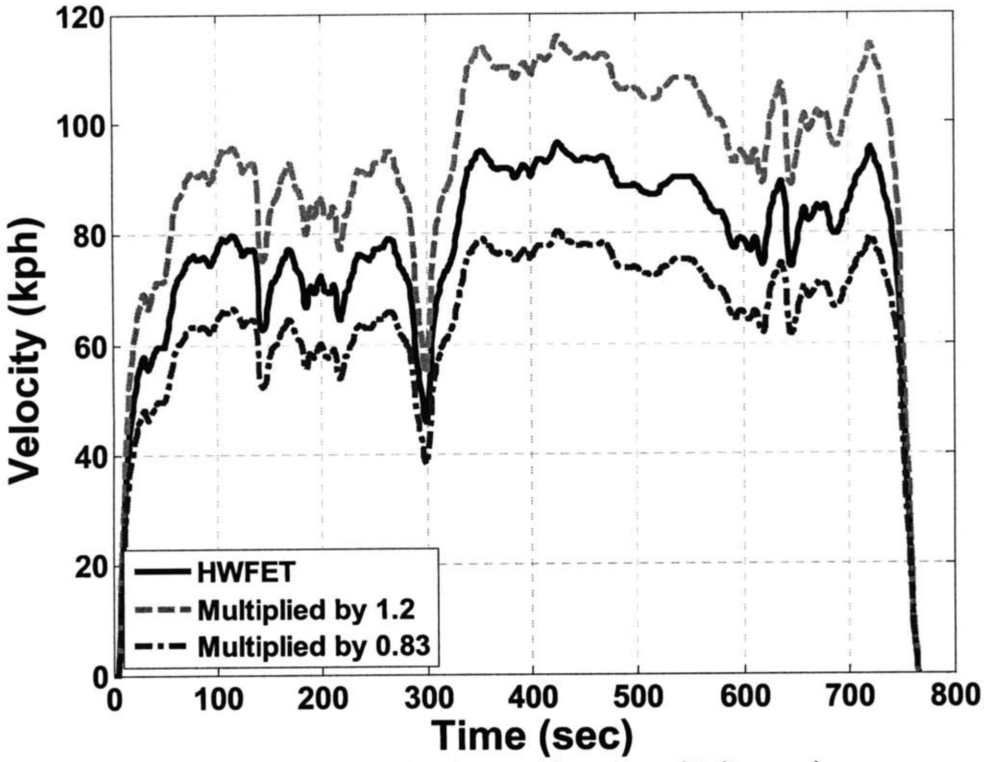

Figure 12: The HWFET drive cycle along with two multiplier cycles

Vehicle Simulation

A wide variety of vehicle simulation types are available and used today. These range from simple, VSP- or micro- based models, to complex programs that trace energy and power flows through all vehicle components and signals. These modeling and simulation tools are becoming more and more critical to the vehicle design and development process. They are also used by traffic engineers and air pollution control professionals to model and predict vehicle emissions in specific locations.

3.2 Methodology for this Project

As discussed in the introduction, there are two sets of issues and questions for this project. The first set relates to how driving style affects fuel consumption, while the second set relates to the aggressiveness of real-world driving. After a review of the research questions, the various methodologies presented above, and the capabilities of the Sloan Automotive Laboratory; a two-pronged methodology was devised. It consists of:

1. Using vehicle simulations and vehicle dynamics to study the sensitivity of fuel consumption to driving aggressiveness and
2. Analyzing driving data to evaluate the aggressiveness of real-world driving styles

3.3 Characterizing How Driving Impacts Fuel Consumption

In addition to determining how specific behaviors impact fuel consumption and the sensitivity of fuel consumption to those behaviors, the main objective of this first component is to develop a metric to quantify driving aggressiveness. The Powertrain System Analysis Toolkit (PSAT) was used to simulate vehicles and speed traces and generate fuel consumption data. Using a simulation program such as this allows all of the other variables that influence fuel consumption to be controlled. While a variety of vehicle models were used for comparison, most of the work relies on the Ford Focus model described below.

Powertrain System Analysis Toolkit

The Powertrain System Analysis Toolkit (PSAT) is a vehicle simulation program developed by Argonne National Laboratory (ANL) with contributions from Ford, General Motors, and DaimlerChrysler. PSAT is a "forward-looking" or "command-based" model that takes transient behavior and control system characteristics into account, providing realistic fuel economy, emissions, and performance numbers. The PSAT component and vehicle models are validated through a combination of vehicle testing, component testing, and drivetrain testing. PSAT and its component models are developed and validated at ANL in a process closely linked with vehicle hardware benchmarking and testing [DOE, 2004].

Vehicle Models

The vehicle used for the majority of simulations is the Ford Focus with the 145 hp Duratec 2.3L Inline-4 cylinder engine (the engine used in the ZTS, ZTW, and ZX3/ZX5 Premium models) with 4-speed automatic transmission, front-wheel drive, and 3022 lb test weight. This vehicle model was validated (to within 5 percent) by ANL using test data collected at the Advanced Powertrain Research Facility for 0 to 60 mph acceleration and both the city and highway drive cycles [DOE, 2004]. Table 7 compares the PSAT model to the published results.

Table 7: Comparison of the Focus PSAT model and actual vehicle; from [DOE, 2004]

MY2004 Ford Focus	HWFET (mpg)	UDDS (mpg)	0-60 mph Time (sec)
PSAT Simulation Results (ANL)	37.36	27.95	11.6
Actual Test Results	37.83	27.92	11.0

Three other vehicles are used for comparison. These include a subcompact (the Honda Civic), a midsize vehicle (the Honda Accord), and an SUV (the Ford Explorer). All of these models were created by ANL and provided with PSAT. No adjustments were made. The basic characteristics of all four vehicles are summarized in Table 8. While weight ranges from 2,711 to 4,530 lbs; power-to-weight ratios range from only 0.042 hp/lb to 0.048 hp/lb.

Table 8: Summary of Vehicle Power and Weights

	Civic	Focus	Accord	Explorer
Test Weight (lb)	2711	3022	3432	4530
Horsepower (hp)	115	144	161	210
Power-to-weight (hp/lb)	0.042	0.048	0.047	0.046
Transmission type	Auto	Auto	Auto	Auto
Number of Gears	4-spd	4-spd	5-spd	5-spd

Driver Model

PSAT, as a forward-looking simulation program, includes a driver model which takes the desired speed trace and generates pedal position and torque commands which control the various vehicle components. The PSAT driver model is a simplistic PI (proportional-integral) controller based on vehicle speed. Figure 13 shows a small section of the NY City Traffic drive cycle along with the actual speed traces driven by the Focus, Civic, and Explorer. Although the same driver model is used for each vehicle, there is slight variation in the actual speed trace, as with dynamometer testing of actual vehicles. As discussed in Chapter 2, this variability contributes to the overall fuel economy shortfall. For this work, the output speed of the simulation, not the input speed trace, was assessed. When simulations were not run, for example when assessing the real-world data, the logged data itself was used.

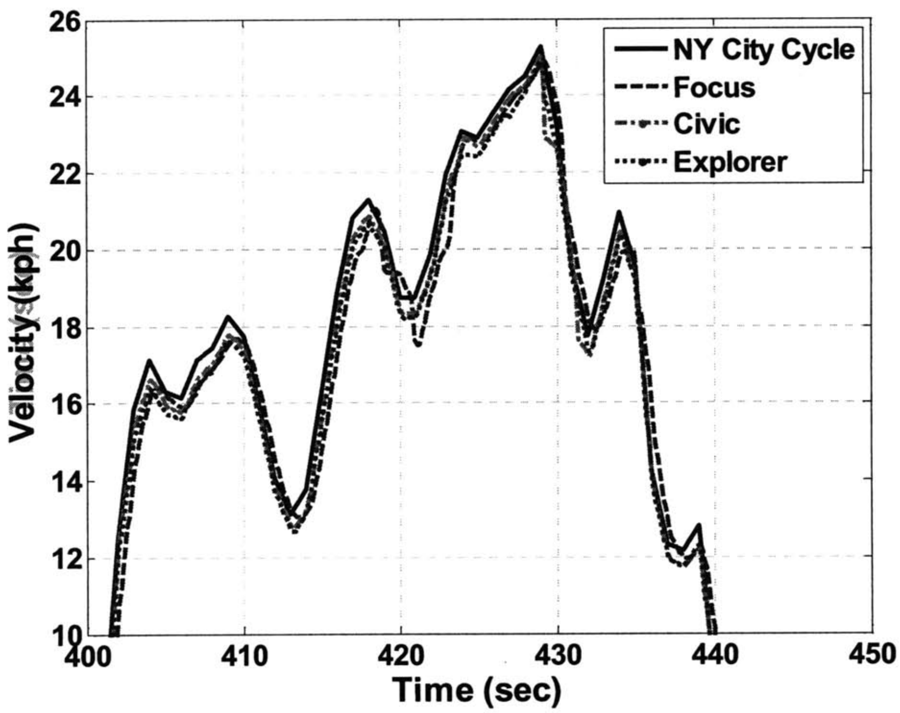

Figure 13: A 50 second segment of the NY City Traffic drive cycle along with the actual speed traces of the Ford Focus, Honda Civic, and Ford Explorer

Speed Traces

Over 1,100 speed traces were simulated with the Ford Focus, including regulatory drive cycles from around the world, a number of real-world driving patterns, and a large set number of modified drive cycles. Figure 14 demonstrates the variety of the speed traces, plotting average acceleration versus average speed.

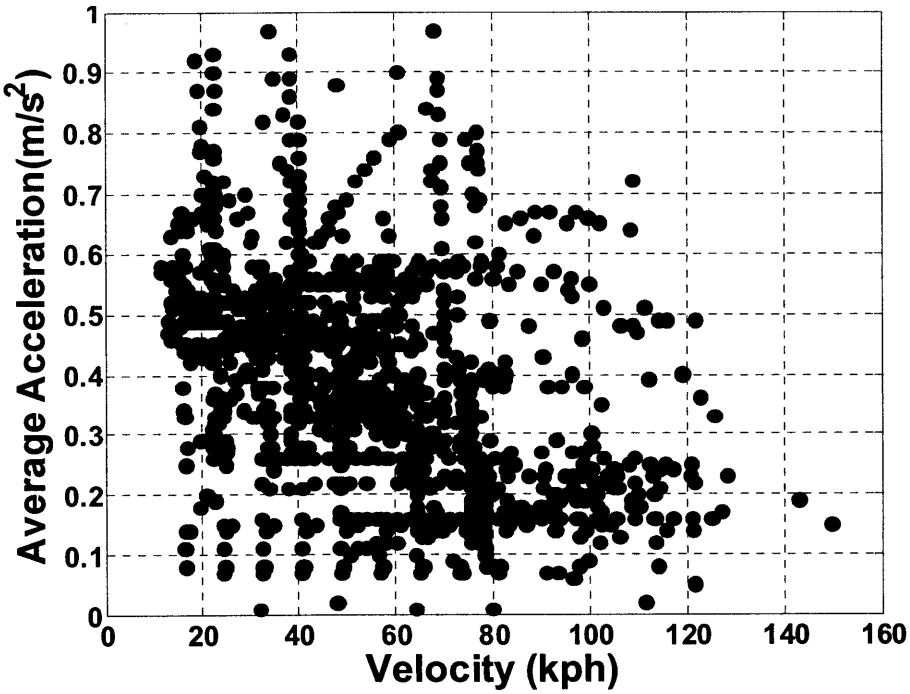

Figure 14: Average acceleration and average velocity of the 1,100 speed traces simulated

Regulatory Drive Cycles

The regulatory drive cycles simulated include all of the EPA "5-cycle" cycles, as well as the European and Japanese regulatory cycles. In addition, four other U.S. and eight other European drive cycles are simulated. For the U.S., these are the cycles developed in the 90s to represent more aggressive driving and include the US06 which was recently incorporated into the EPA fuel economy test. For Europe, these are eight of the INRETS drive cycles developed as part of the DRIVE project sponsored by the E.U. Directorate General XIII [Andre et al., 1994]. The basic characteristics of all of these cycles are summarized in Table 9.

Table 9: Comparison of U.S., European, and Japanese Driving Cycles

	Percent idle (%)	Distance (km)	Average speed (kph)	Maximum speed (kph)	Maximum acceleration (m/s^2)
			U.S. "5-cycle" Cycles		
FTP	18.9	12.0	31.5	91.2	1.6
HWFET	0.9	16.5	77.5	96.4	1.4
US06	7.5	12.9	77.2	129.2	3.2
SC03	18.7	5.8	34.9	88.2	2.2
C-FTP	18.9	12.0	31.5	91.2	1.6
			U.S. Other Drive Cycle		
LA92	15.1	15.7	39.4	107.5	2.8
REP05	3.4	32.1	82.4	128.5	3.1
ARB02	7.5	31.7	69.6	128.5	3.2
			Japanese Cycles		
10/15 mode	2.6	0.4	25.4	70.0	0.3
10 mode	3.7	0.1	16.9	40.0	0.8
15 mode	1.7	0.2	41.8	70.0	0.4
			European Regulatory Cycles		
ECE	34.5	1.0	18.2	50.1	1.1
EUDC	8.2	7.0	64.0	120.1	0.8
NEDC	24.9	11.0	33.6	120.1	1.1
			Other European Cycles		
INRETS urban	24.6	3.5	22.3	57.2	2.1
INRETS urban1	26.9	4.2	20.9	59.0	2.2
INRETS urban3	21.3	2.9	18.0	61.6	2.1
INRETS road	10.4	11.2	47.9	103.4	2.2
INRETS road1	9.3	7.8	40.2	71.7	2.4
INRETS road2	3.2	27.3	65.8	125.8	2.2
INRETS hwy	3.4	46	92	138	2.6
INRETS hwy1	7.5	42.7	82.3	150.0	3.2

Real-World Driving Patterns

Over 800 real-world driving patterns were collected in Boston, Massachusetts and Greensboro, North Carolina to serve as examples of real-world driving data. Vehicle speed was logged from the CAN-bus of vehicles using Davis Instruments, Inc CarChips. In addition to serving as a trial of real-world driving (discussed in more detail below), this data was processed into speed traces for use with PSAT. A sample trace is shown in Figure 15. In total 824 trips were collected. However, only 155 were simulated in PSAT to yield fuel consumption results.

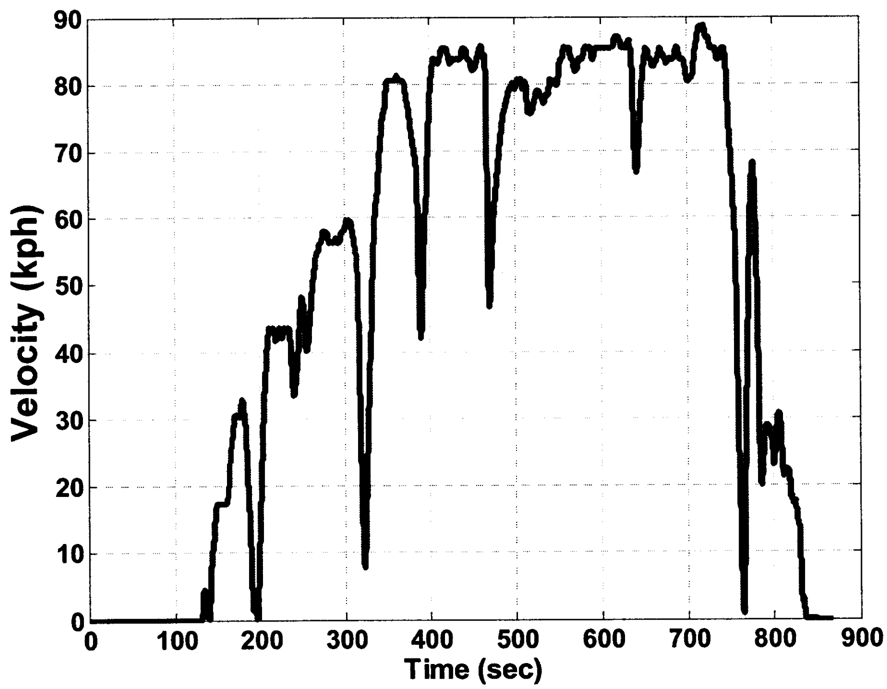

Figure 15: A 900 second real-world driving pattern logged with a CarChip

Modified Speed Traces

For this work, instead of testing just "multiplier" drive cycles in which the speed trace alone is scaled, speed traces were modified to scale 1) velocities, 2) accelerations, and 3) both. Velocity-scaling was achieved by multiplying both the speed and time vectors by a scaling factor. As shown in Figure 16, as the maximum velocity increases, so do the length and distance of the cycle, in order to maintain the same accelerations. However, these modifications mean that the accelerations now occur at higher speeds. Acceleration-scaling was achieved by multiplying the time vector by a scaling factor, as shown in Figure 17. Velocities remain the same; however, both velocities and accelerations last longer, and the cycle travels a longer distance. Scaling both acceleration and velocity was achieved through the standard "multiplier" method in which only the speed trace is scaled, not the time vector. In total, twelve standard and real-world cycles were modified and used in vehicle simulations. The original cycles are summarized in Table 10 below. Each is modified in all three ways with scaling factors from 0.5 to 2.0.

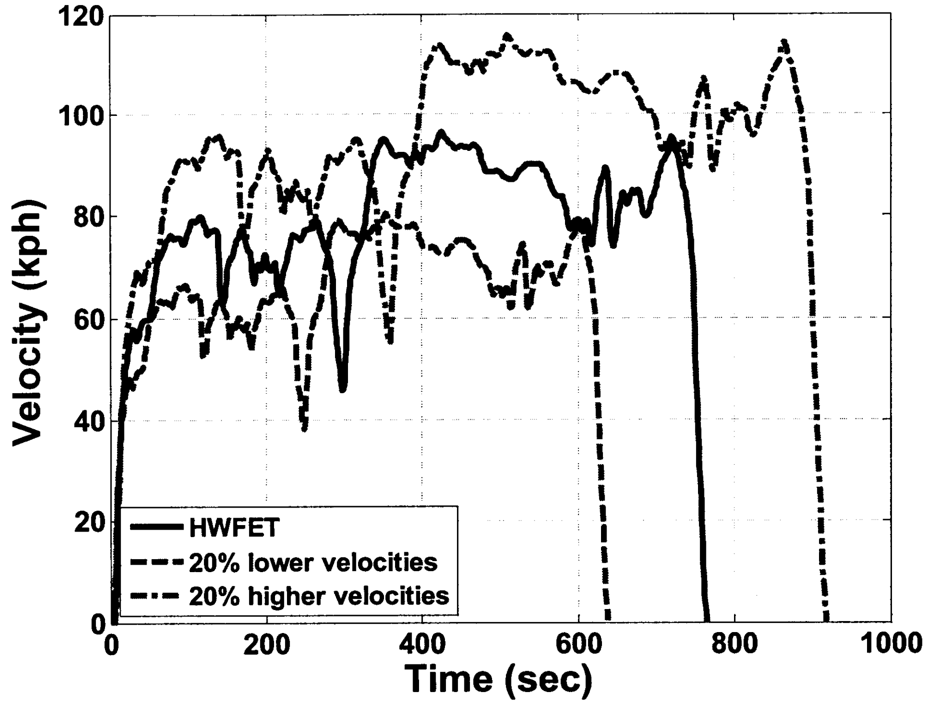

Figure 16: Velocity-modified HWFET speed traces

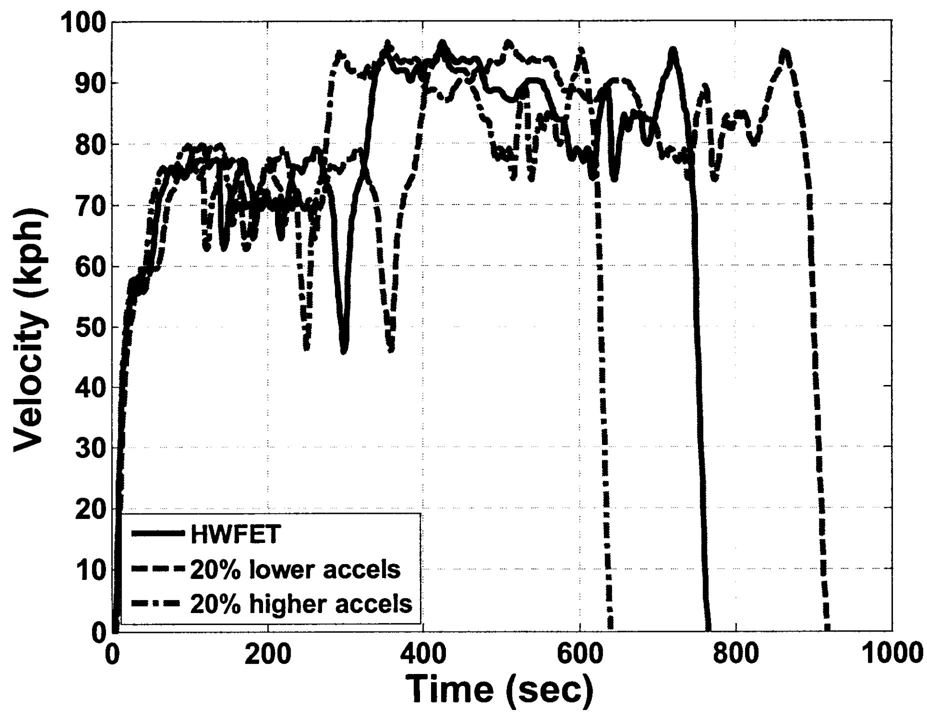

Figure 17: Acceleration-modified HWFET speed traces

Table 10: Basic characteristics of the ten speed traces scaled for velocity, acceleration, and both velocity and acceleration

Speed Trace	Average Speed Of Original Cycle (kph)	Maximum Speed Of Original Cycle (kph)	Maximum Acceleration Of Original Cycle (m/s^2)
Standard Drive Cycles			
HWFET	77.5	96.4	1.4
UDDS	31.5	91.2	1.6
US06	77.2	129.2	3.2
LA92	39.4	107.5	2.8
REP05	82.4	128.5	3.1
ARB02	69.6	128.5	3.2
Real-world Driving Patterns			
Trip 79	63.7	104.9	1.9
Trip 80	74.9	109.7	2.0
Trip 81	21.4	55.7	2.0
Trip 82	37.8	72.7	2.4

Steady-Speed Speed Traces

Steady-speed traces were developed to simulate driving at steady-speeds, with no accelerations. These speed traces are identified by the cruise speed. In order to start from zero initial speed, these cycles consist of an initial acceleration period of varying distance and time, but at a consistent acceleration rate (0.8 m/s^2). This period is followed by 40 km of driving at steady-speed. The duration of the speed trace therefore depends on the cruise speed. For example, the 50 mph steady-speed trace lasts roughly 30 minutes while the 25 mph trace lasts close to an hour. Figure 18 shows the first 200 seconds of these two speed traces.

Because of the way the traces are created, as cruise speed increases, the average acceleration increases, as shown in Figure 19, and the average speed of the entire cycle decreases slightly, as shown in Figure 20. For example, the 90 mph (145 kph) steady-speed trace has an average speed of 88 mph (141 kph) and an average acceleration close to 0.04 m/s^2.

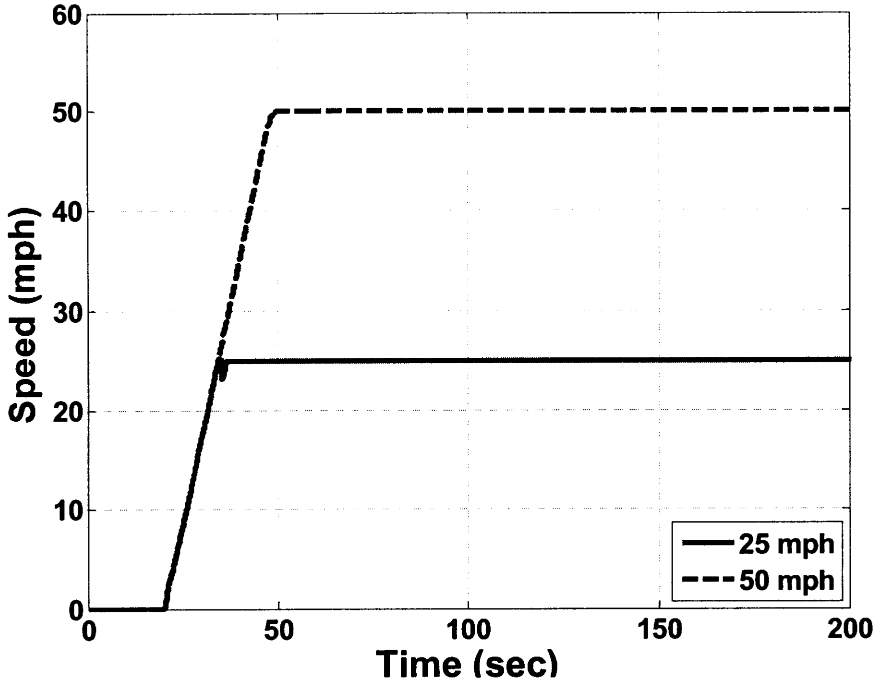

Figure 18: The first 200 seconds of the 25 mph and 50 mph steady-speed traces

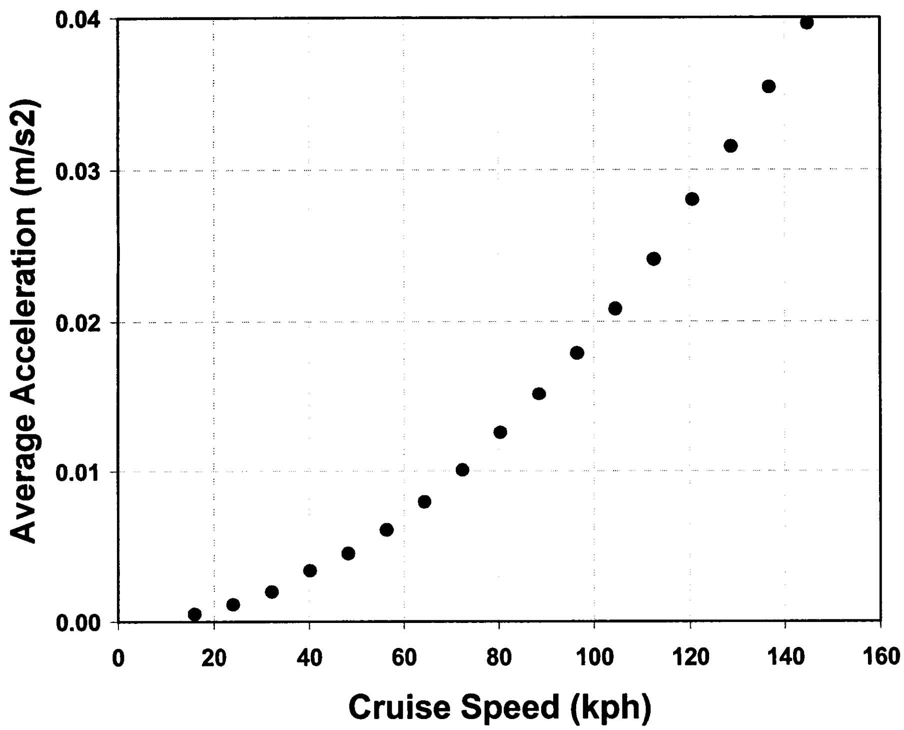

Figure 19: Average acceleration versus cruise speed for the steady-speed traces

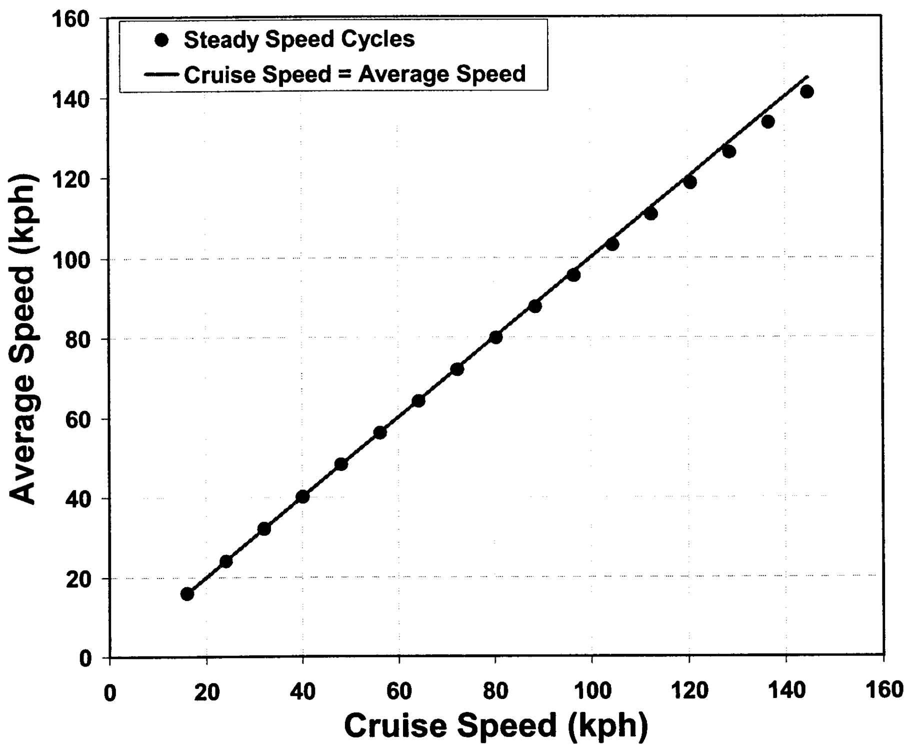

Figure 20: Average speed versus cruise speed for the steady-speed traces

3.4 Assessing Real-World Driving

To assess real-world driving and how driving aggressiveness is related to vehicle performance, driving patterns from two sources were analyzed:

1. The 100-Car Naturalistic Driving Study
2. Driving patterns logged using CarChips around Boston, MA and Greensboro, NC

Each data set has both limitations and strengths. The 100-Car Study is much larger and is sorted by vehicle performance, but only processed data is available. This is the primary data set used to assess real-world driving. The CarChip data is smaller, but the raw speed traces are available. It is used primarily to provide real-world driving patterns for use with PSAT and to assess the distribution of driving styles by trip.

The 100-Car Study

The 100-Car Study was one of the first instrumented-vehicle studies designed explicitly to collect large-scale, naturalistic driving data. It is part of a larger effort to support the Transportation Research Board's Strategic Highway Research Program (SHRP 2). This study was completed by the Virginia Tech Transportation Institute (VTTI) and sponsored by the National Highway Traffic Safety Administration (NHTSA), Virginia Tech, Virginia Department of Transportation, and Virginia Transportation Research Council. As with other naturalistic driving studies, drivers were given no special instructions, no experimenter was present, and the data collection instrumentation was unobtrusive. As discussed above, naturalistic driving studies can not isolate any one factor affecting driving style. However, of the 100-Car Study, all of the data was collected in the same area, Northern Virginia/Metropolitan Washington, DC. Because of this, variation due to traffic and roadway conditions is lower than if multiple geographic locations were included. Therefore, although the data is not likely to represent average U.S. driving, it is better for correlating differences in driving style by vehicle characteristics.

Data Collection

As part of the study, VTTI collected naturalistic driving data from 100 vehicles in the Northern Virginia area for over one year (2005). In total, over 2 million miles and almost 43 thousand hours of driving patterns were logged. However, for this study, 79 thousand miles of this data was analyzed. The 100-Car Study set does not represent average U.S. driving. It is, if anything, more aggressive since 1) the Washington, DC/Northern Virginia area has higher traffic and congestions that the rest of the U.S. and 2) the drivers selected for the study were purposely chosen to increase the likelihood of accidents, instead of to maintain the age and gender distributions of the driving population. Specifically, a higher percentage of younger drivers were included. However, extreme drivers, both very safe and very unsafe, were avoided, and all drivers under 18 were excluded. Table 11 summarizes the distribution of ages and genders of the 109 primary drivers of the study. Two-thirds were male and one-third were female [Dingus et al., 2006].

Table 11: Distribution of genders and ages of primary drivers in the 100-Car Study; from [Dingus et al., 2006]

Age		Female	Male	Total
18-20	N	9	7	16
	%	8%	6%	15%
21-24	N	11	10	21
	%	10%	9%	19%
25-34	N	7	12	19
	%	6%	11%	17%
35-44	N	4	16	20
	%	4%	14.7%	18%
45-54	N	7	13	20
	%	6%	12%	18%
55-75	N	5	8	13
	%	5%	7%	12%
TOTAL	N	43	66	109
	%	39%	61%	100%

The data collected included five channels of video and vehicle kinematics. For this work, only the vehicle speed and acceleration data was used. Vehicle speed was logged with both CAN and GPS. However, the CAN-based measurements were more reliable over the entire study. The GPS data was used primarily to detect outliers in the CAN data [Dingus et al., 2006].

For practical reasons, VTTI limited the number of specific vehicle models in the 100-Car Study to six, those listed in Table 12. There was a significant under representation of SUVs in the study relative to the representation in the total vehicle fleet [Dingus et al., 2006].

Table 12: The six vehicle makes and models included in the 100-Car Study

Make	Model	Model Years	Privately owned or leased?	Number of Vehicles
Ford	Explorer*	1995 – 2001	Privately owned	15
	Taurus*	1996 – 1999, 2000 - 2002	Privately owned	12
Chevy	Cavalier	2002	Leased	17
	Malibu	2002	Leased	21
Toyota	Camry	1997 – 2001	Privately owned	17
	Corolla	1993 – 2002	Privately owned	18

*Because the Mercury Mountaineer and Mercury Sable have the same body style as the Ford Explorer and Ford Taurus, respectively and were included with these vehicles.

Most vehicle models are offered with several engine options. When the variations in power-to-weight ratio are included, the 100 vehicles of the study can be divided into eleven distinct vehicle groups, listed in Table 7. In doing this, two vehicles are excluded since, out of the entire set, only one vehicle at the specific model and power-to-weight ratio was included. Additionally, for the Ford Explorer and Toyota Camry, vehicles with small differences in either weight or engine power were grouped together. Of the eleven groups, the Explorer, Camry, and Malibu are sorted into two power-to-weight ratios, and the Ford Taurus is sorted into three groups. In total, power-to-weight ratio varies from 0.036 to 0.062 hp/lb. Separating the vehicles into these groups allows driving style to be assessed by power-to-weight ratio. However, as shown, both the number of vehicles and the distance analyzed vary between groups. Because only a sub-set of the 100-Car Study data was analyzed and because those files were selected randomly within each group, the distance analyzed for each group varies less than the number of vehicles in the group.

Table 13: Specifications of the vehicle groups identified in the 100-Car Study; based on Vehicle Identification Numbers

	Make and Model	Power (hp)	Curb Weight (lbs)	Power-to-weight (hp/lb)	EPA Fuel Economy City/ Highway (MPG)	Number of Vehicles	Distance Analyzed (km)
1	Ford Explorer	160	3,800/4,100	0.036/0.039	16/20	4	4,501
2	Ford Taurus	145	3,500	0.038	20/28	7	9,805
3	Chevy Cavalier	115	2,600	0.040	23/29	13	10,248
4	Toyota Camry	133/136	3,000	0.040/0.041	23/32	14	5,448
5	Chevy Malibu	150	3,000	0.0455	22/30	6	2,364
6	Toyota Corolla	125	2,400	0.046	28/33	18	7,180
7	Ford Explorer	205/210	3,800/4,100	0.047/0.050	15/20	11	8,908
8	Chevy Malibu	170	3,000	0.052	20/29	15	9,659
9	Ford Taurus	200	3,500	0.053	19/28	3	6,257
10	Toyota Camry	194	3,200	0.055	20/27	4	5,029
11	Ford Taurus	235	3,500	0.062	17/26	3	9,964
TOTAL						**98**	**79,363**

Data Processing

A sub-set of vehicle speed and acceleration data from the 100-Car Study was processed into speed-acceleration frequency distributions (SAFDs). First, the data was cleaned by VTTI to eliminate files with possible instrumentation errors. Specifically, both the CAN- and GPS-based speed measurements and the accelerometer- and speed-based acceleration values were compared to detect outliers. Data marked by instrumentation failure was removed, along with trips less than 2 minutes [VTTI, 2009].

After cleaning, 8,890 trip files were randomly selected and stratified across the eleven vehicle groups, without consideration of environmental factors such as roadway type or traffic density. A SAFD was generated for each group, accumulating the driving data from all of the vehicles and drivers in that group. The SAFDs express the amount of time spent in specific speed and acceleration bins. The velocity scale was partitioned into 20 bins of 5 mph (8 kph) from 0 to 100 mph (160 kph). The longitudinal acceleration scale was partition into 0.1 g (0.98 m/s^2) bins [VTTI, 2009]. The 11 resulting SAFDs were analyzed both individually and as an accumulated total.

CarChip Driving Patterns

A number of real-world driving patterns were collected from drivers and vehicles using Davis Instruments' CarChips such as the one shown in Figure 21. These driving patterns were used to provide a wider range of driving styles for the vehicle simulation step and to provide illustrative distributions of driving data and driving aggressiveness for this step.

Figure 21: A Davis Instruments CarChip; Source: www.carchip.com

Data collection

The Davis Instruments' CarChips can log over 20 parameters and up to 300 hours of driving data, depending on the number of parameters logged and the logging intervals. Vehicle speed can be logged with a resolution of up to 1 kph and a frequency of up to 1 sample per second. All other parameters can only be logged every 5 seconds [Davis Instruments, 2007]. For this work, only vehicle speed was logged, at its maximum resolution and frequency. A total of 824 trips covering 12,620 km were collected from 15 different vehicles, as summarized in Table 14.

Table 14: Summary of driving patterns collected using the CarChips

Month and Year	General Location	Number of Vehicles	Number of Trips	Distance (km)
Sept – Oct 2008	Boston, MA	4	39	1,160
Nov 2008 – Jan 2009	Greensboro, NC	3	70	1,470
March – April 2009	Boston, MA	5	373	5,580
May – June 2009	Boston, MA	1	197	2,110
June – July 2009	Boston, MA	2	145	2,290

Processing

First, the CarChip vehicle speed data was up-sampled, filtered, and then down-sampled to increase the resolution above 1 kph, but maintain the 1 second sampling rate. Figure 21 shows 100 seconds of a raw and processed CarChip speed trace. Accelerations were calculated by taking the derivative of the processed vehicle speed trace. Because the trip data is directly available, the CarChip data was not generated into SAFDs. The speed traces themselves were assessed. Specifically, the data was used to provide illustrative distributions of trip distance, average speed, and driving aggressiveness.

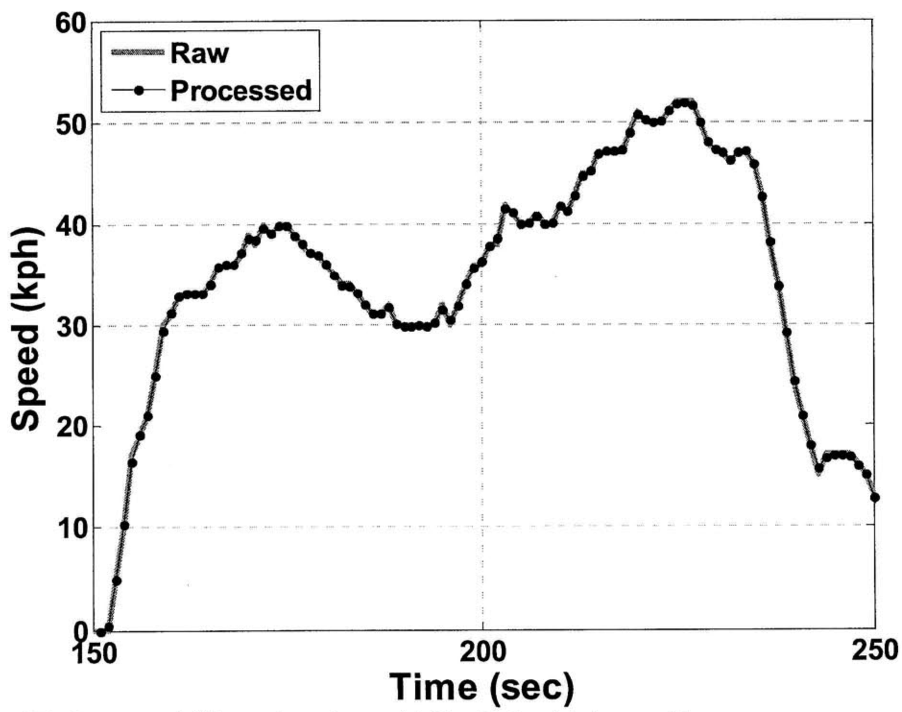

Table 15: Raw and filtered real-world CarChip driving pattern

4 Drive Cycle Dynamics

This chapter delves into the drive cycle dynamic variables of tractive force, tractive power, and wheel work. These variables capture the force, power, and energy required at the wheels during driving. It is important to understand these variables and how they are calculated. Later, in Chapter 5 and Chapter 6, average velocity, tractive power, and wheel work will be related to fuel consumption and used to quantify driving aggressiveness. This chapter will explain how those variables are calculated from velocity and accelerations so that, later, acceleration and velocity can be related to fuel consumption. Throughout this chapter, six standard drive cycles are used as examples. These are the FTP, HWFET, US06, LA92, ARB02, REP05, NY_City, and SC03, which were described briefly in Chapter 2.

4.1 Tractive Force

Tractive force is the force required at the wheels during driving. There are two common equations for calculating tractive force (Equations 10 and 11). The first, Equation 10, calculates the total tractive force by summing the force required at the wheels due to rolling, aerodynamic, and grade resistance and inertia:

$$F_{TR} = \underbrace{(C_r \cdot M \cdot g)}_{\text{rolling resistance}} + \underbrace{\left(\frac{C_D \cdot A_F \cdot v^2 \cdot \rho}{2}\right)}_{\text{areodynamic resistance}} + \underbrace{(M \cdot g \cdot \sin\alpha)}_{\text{grade resistance}} + \underbrace{(M \cdot \delta \cdot a)}_{\text{linear and rotational inertia}} \tag{10}$$

Where, in the rolling resistance term, C_r is the coefficient of rolling resistance for the vehicle, M is the vehicle test mass (curb mass plus 300 lbs), and g is gravitational acceleration. In the term for aerodynamic drag, ρ is the density of air (taken as constant 1.2 kg/m^3), C_D is the coefficient of drag, A_F is the frontal area of the vehicle, and v is vehicle speed. In the grade term, θ is the angle of the road grade and $sin\theta$ is the grade. In the inertia term, δ is a mass correction factor which accounts for the fact that the 4 rotating wheels must be angularly as well as linearly accelerated and is assumed constant at 1.04.

The alternative, Equation 11, relies on the coastdown coefficients of the vehicle and works only when there is no grade:

$$F = \underbrace{(A + Bv + Cv^2)}_{\textit{road load}} + \underbrace{(M\delta a)}_{\textit{inertia}} \tag{11}$$

Where the A coefficient comes partially from the rolling resistance of the tires, but also includes accessory loads and drag from the brake pads and wheel bearings. The B coefficient includes part of the rolling resistance from the tires, but also the power used by the various pumps of the vehicle. The C coefficient is the coefficient for aerodynamic drag including the frontal area and the density of air. This is the equation used throughout this study. Vehicle weight effects in rolling resistance are included in the A and B values. So when the weight of a vehicle is increased, these coefficients change as well. The "ABC coefficients" can be determined directly from a simple vehicle test, a coastdown test. This procedure is described in SAE J1263. The curb weight and coastdown coefficients for the Honda Civic, Ford Focus, Honda Accord, and Ford Explorer (the vehicle models used in this study) are summarized in Table 16. The coefficients for the Ford F-150, Chevy Equinox, and Toyota Prius PSAT models are provided for reference.

Table 16: Curb weight and ABC coefficients of representative PSAT vehicle models

Vehicle	Civic	Focus	Accord	Explorer	Prius	F-150	Equinox
Curb Weight (lb)	2,711	3,022	3,432	4,530	3,194	5,511	4,008
A Coefficient (N)	96.5	133.1	121.9	181.4	64.1	107.7	143.5
B Coefficient (N·s/m)	1.4	5.05	1.83	2.42	2.2	10.66	8.08
C Coefficient ($N \cdot s^2/m^2$)	0.40	0.37	0.42	0.62	0.41	0.90	0.51

The sum of the A, B, and C terms in Equation 11, or the sum of the rolling, aerodynamic, and grade resistances in Equation 10, is termed the "road-load," as defined in Equation 12. This is the force at the wheels under steady-speed driving, excluding all inertia forces:

$$Roadload(v) = A + Bv + Cv^2 \tag{12}$$

Tractive force can be either positive or zero or negative. As clearly described by Sovran and Blaser [2003], based on this, there are three distinct "modes" of driving. Powered-driving occurs when the total tractive force is positive. Powered deceleration occurs when total tractive force is positive and the vehicle is decelerating. In this mode, inertia force is negative, but the force from velocity is enough to overcome it. Non-powered driving occurs when the vehicle is stationary or when inertia force is negative and greater than the tractive force.

4.2 Tractive Power

Having defined tractive force, tractive power is simply the tractive force times the vehicle speed and given in Equation 13 for the coastdown coefficient approach:

$$P = \underbrace{\left(Av + Bv^2 + Cv^3\right)}_{road\ load\ power} + \underbrace{\left(M\delta av\right)}_{inertia\ power} \tag{13}$$

As with tractive force, tractive power can be separated into velocity and acceleration (or inertia) components. The average positive power, which we will use later to describe driving patterns, is simply the mean of tractive power when tractive power is positive, defined in Equation 14:

$$\overline{P} = \frac{\int \left(Av + Bv^2 + Cv^3 + Mav\right)^{+} dt}{\int t^{P>0} dt} = \frac{\int (P)^{P>0} dt}{\int t^{P>0} dt} \tag{14}$$

4.3 Wheel Work

Wheel work is the positive energy (or work) required at the wheels, expressed per unit distance. Wheel work is calculated using Equation 15, by dividing the total positive tractive power by the *total* distance traveled (not just the distance traveled when tractive power is positive). Unlike tractive force or power, wheel work is always positive.

$$W_{wheel} = \left(\frac{E}{x}\right) = \frac{\int \left(Av^3 + Bv^2 + Cv + Mav\right)^{+} dt}{\int vdt} = \frac{\int (P)^{P>0} dt}{\int vdt} \tag{15}$$

Figure 22 shows the total tractive power and velocity profile for a 150 second section of the LA92 drive cycle. The shaded area represents positive power. The wheel work for this specific section of the LA92 is the sum of this shaded area divided by the distance traveled (the sum of the velocity profile).

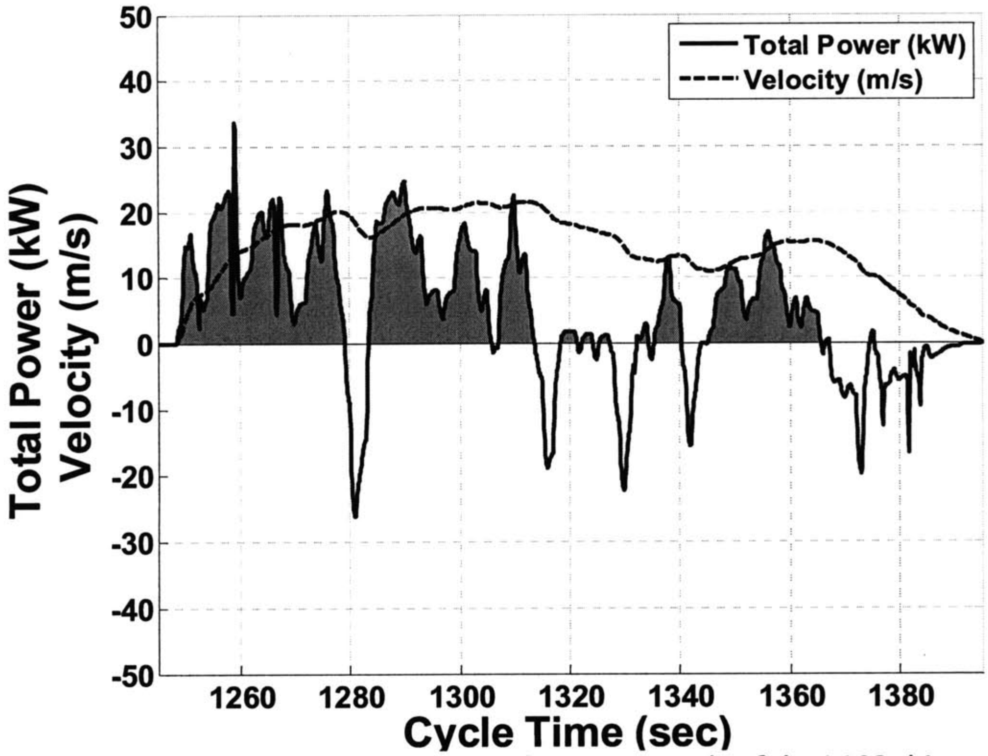

Figure 22: Tractive power and velocity for 150 seconds of the LA92 drive cycle

As above, wheel work can be separated into velocity ("road-work") and acceleration ("inertia-work") components. "Road-work" is the road load power summed when total power is positive and expressed per unit distance traveled. It is defined by Equation 16. This power is shown in Figure 23 for the same 150 seconds of the LA92. Because inertia effects are excluded, road-work is always positive and proportional to velocity.

$$W_{wheel,velocity} = \frac{\int \left(Av^3 + Bv^2 + Cv\right)^{P>0} dt}{\int vdt} \tag{16}$$

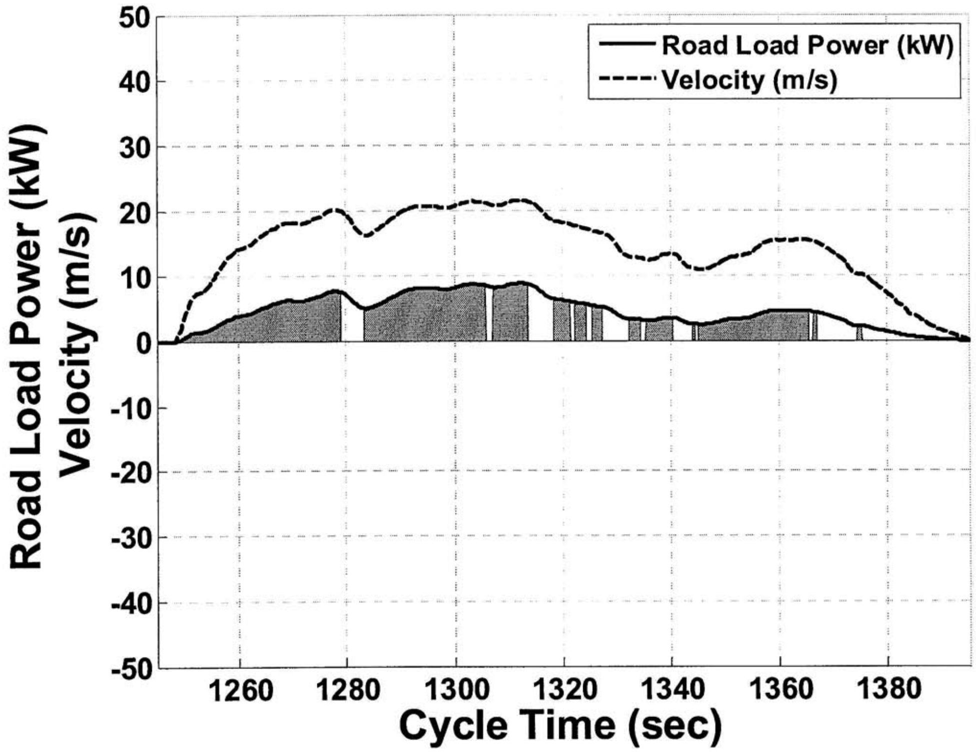

Figure 23: Road-load power and velocity for 150 seconds of the LA92 drive cycle

"Inertia- work" is the inertia power summed when *total* power is positive and expressed per unit distance traveled, as defined by Equation 17. This power is shown in Figure 24, for the same 150 seconds of the LA92. Note that some negative inertia power is included, for times when total power is positive.

$$W_{wheel,Inertia} = \frac{\int (Mav)^{P>0} dt}{\int v dt} \quad (17)$$

For any driving pattern or section of a driving pattern, the total wheel work is the sum of the road-work and inertia-work components of wheel work, as defined in Equation 18:

$$W_{wheel} = W_{wheel,Velocity} + W_{wheel,Inertia} \quad (18)$$

As with acceleration, velocity, relative positive power, and other metrics; none of average force, average power, or wheel work or any of their components correlate with fuel consumption.

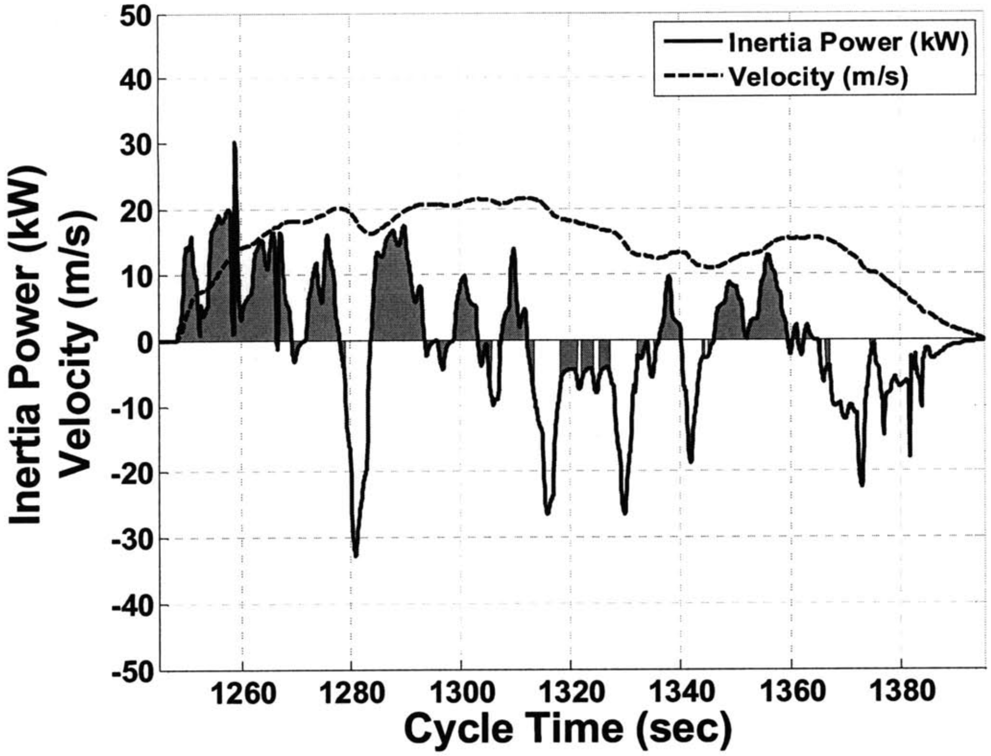

Figure 24: Inertia power and velocity for 150 seconds of the LA92 drive cycle

4.4 Clarifications on Wheel Work and Average Power

There are subtleties in how wheel work and average power are calculated that are very important in order to properly interpret and use these values. This section explains several of these subtleties.

1. *The "road- work" of a driving pattern is not the same as the steady-speed wheel work at the average speed of the driving pattern*

Road-work, as defined above in Equation 16, sums road-load power only when total power is positive, as shown in Figure 23. In contrast, the steady-speed wheel work is the positive tractive energy per unit distance during steady-speed driving. With no accelerations, tractive power is always positive during steady-speed driving. Consequentially, steady-speed wheel work simplifies to instantaneous road-work at a specific velocity, which is proportional to road-load:

$$W_{wheel,Steady} = \frac{\int \left(Av + Bv^2 + Cv^3\right)dt}{\int vdt} = \frac{\left(A\bar{v} + B\bar{v}^2 + C\bar{v}^3\right)}{\bar{v}} \propto Roadload(\bar{v}) \qquad (19)$$

In addition, road-load and road-load power are non-linear relative to velocity. Because, road-work calculations sum the road-load power over all speeds, instead of just average speed, these non-linearities further contribute to differences between road-work and steady-speed wheel work. This difference is shown in Figure 25 for the six sample drive cycles.

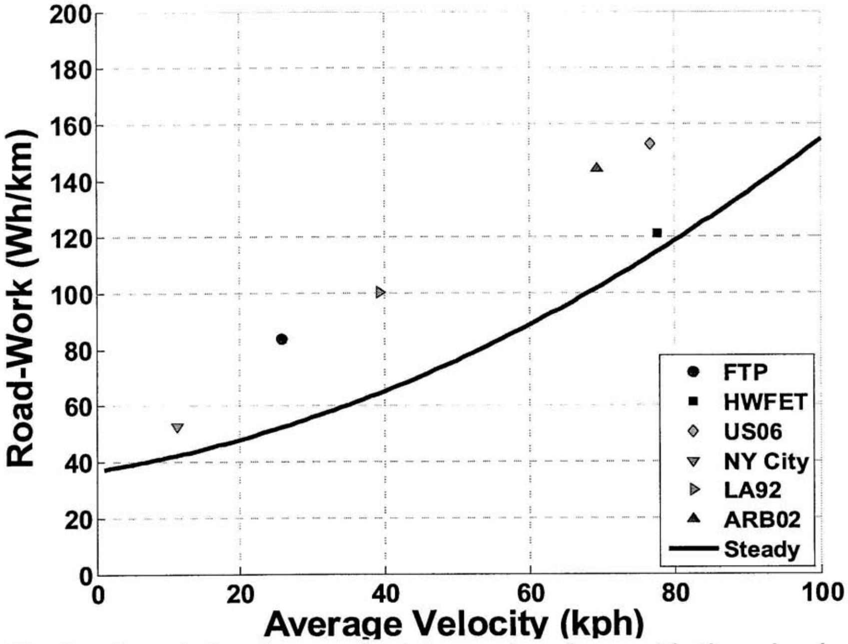

Figure 25: Road-work for six sample drive cycles along with the wheel work of steady-speed driving against velocity

Following from this, it is simple to observe that inertia wheel work (Equation 17 above) is not the same as wheel work minus steady-speed wheel work at the average speed of the drive cycle. The difference between actual wheel work and steady-speed wheel work at average speed reflects not just the role of acceleration in wheel work, but also the impact of variations and fluctuations in speed. This value is the true "acceleration wheel work" since it includes all of the impacts from acceleration (or change in speed) on wheel work. It is defined in Equation 20 and demonstrated for the six sample drive cycles in Figure 26. For all but one of the cycles shown, the acceleration wheel work (y-axis) is greater than the inertia wheel work (x-axis). The low speed and high inertia wheel work of the NY City Traffic drive cycle mean that instead of increasing the acceleration wheel work, speed variations decrease it, relative to inertia wheel work. For the HWFET, the inertia wheel work and the acceleration wheel work are approximately the same. This is because of the very low accelerations of this cycle.

$$\left(\frac{E}{x}\right)_{accel} = \left(\frac{\int \left(Av^3 + Bv^2 + Cv + Mav\right)^+ dt}{\int v dt}\right) - \left(Roadload(\bar{v})\right) \tag{20}$$

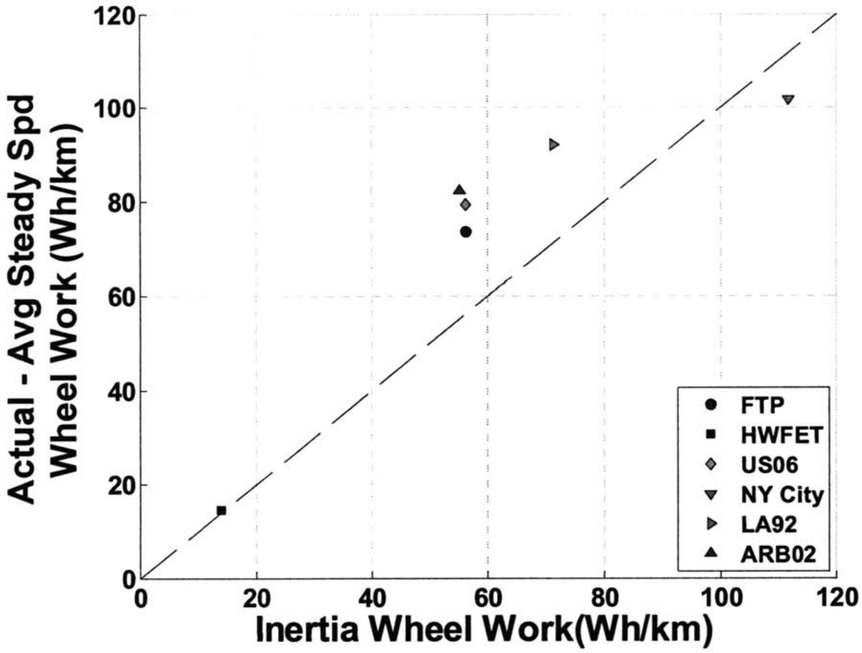

Figure 26: Acceleration wheel work versus inertia wheel work for six sample cycles

2. *Neither inertia nor acceleration wheel work yield acceleration when divided by mass*

Despite the fact that dividing wheel work by vehicle mass yields units of acceleration, the result does not correlate with average acceleration, as pointed out in Figure 27. This is because in calculating inertia wheel work, inertia power is summed only when total power is positive but divided by total distance traveled. Thus when inertia or acceleration wheel work is divided by mass the result is significantly lower than actual average acceleration.

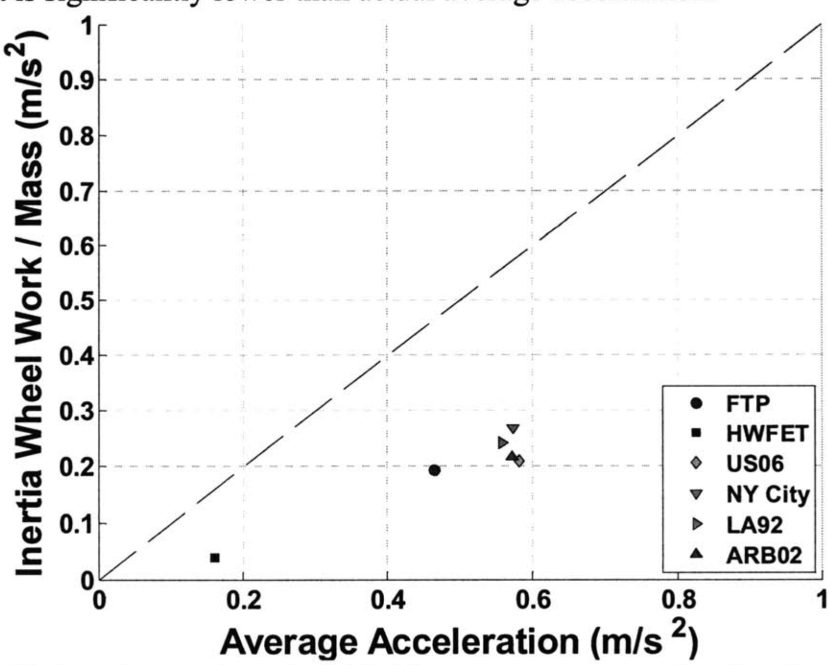

Figure 27: Inertia wheel work divided by mass versus acceleration for six sample cycles

3. Wheel work is not the same as energy consumption

Despite the fact that wheel work and fuel consumption can both be expressed in units of energy per unit distance, they are not equivalent, as shown in Figure 28. Wheel work is measured at the wheel, while fuel consumption is measured before the engine. If vehicle efficiency was always constant, then the two would be linearly related. However, driving conditions have a strong impact on vehicle efficiency, and, as a consequence, wheel work and fuel consumption do not correlate across driving patterns and styles. This will be explored in more detail in the following chapter.

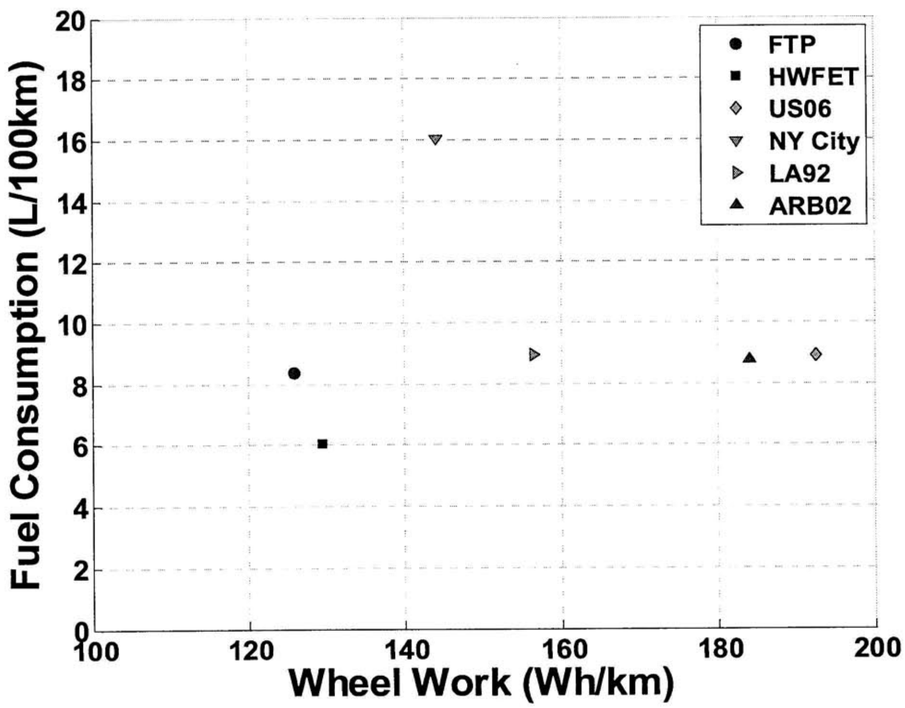

Figure 28: Ford Focus fuel consumption versus wheel work for six sample drive cycles

5 Simulation Results

As discussed in Chapter 3, over 1,100 speed traces were simulated with PSAT and the Ford Focus model to provide data for 1) illuminating how specific behaviors influence the fuel consumption of a conventional vehicle and 2) quantifying driving aggressiveness. This chapter examines the results of those simulation results. It begins by looking at steady-speed driving. Because steady-speed driving represents the simplest and most efficient form of driving for a given speed, this case is examined in depth. The chapter then presents the results from transient speed traces, specifically sets of velocity-scaled and acceleration-scaled speed traces. It ends by examining the trends observed in the entire data set.

5.1 Steady-Speed Driving

The optimal speed trace for fuel consumption is constant- or steady-speed driving. El-Shawarby et al. [2005] found that vehicles get the lowest fuel consumption between 60 and 90 kph (38 and 56 mph), while Wang et al. [2008] observed lowest consumption between 50 and 70 kph (31 and 44 mph). To better understand the effects of speed on fuel consumption, this section looks in-depth at the case of steady-speed driving, using the Ford Focus as a reference vehicle.

Focus Steady-Speed Driving

As shown in Figure 29, the steady-speed fuel consumption of the Ford Focus is lowest at 64 kph (40 mph) and increases with both increasing and decreasing speeds. In addition, there are noticeable jumps in the fuel consumption trend, specifically at around 20 kph, 35 kph, and 60 kph. Although not as dramatic, the slope of the fuel consumption relationship changes at around 150 kph as well. This curve can be explained though the wheel work and efficiency trends.

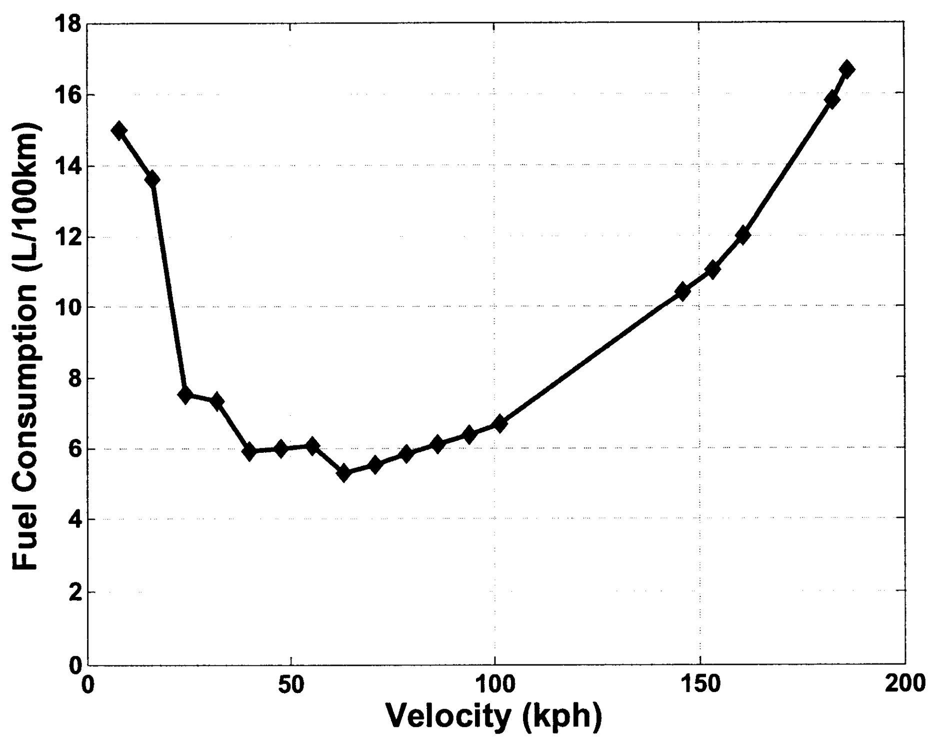

Figure 29: Ford Focus fuel consumption for steady-speed driving; due to an unexplained drop in clutch efficiency between 110 and 140 kph, those points are excluded

Wheel work expresses the efficiency of the speed trace at maximizing distance traveled per unit of energy. And the vehicle efficiency expresses the efficiency of the vehicle at providing energy to the wheels per unit of fuel. As a result, wheel work divided by efficiency is proportional to fuel consumption, as shown in Figure 30 for steady-speed driving. In order to understand steady-speed fuel consumption, the following sections examine the steady-speed driving dynamics and efficiencies of the Ford Focus.

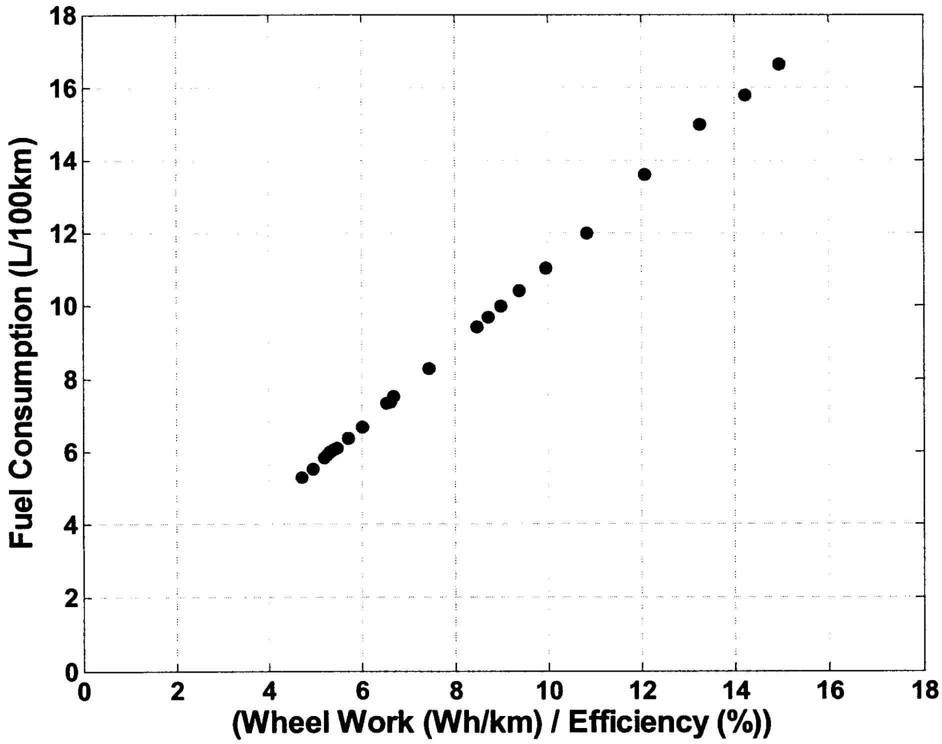

Figure 30: Fuel consumption versus wheel work divided by efficiency for steady-speed driving by the Ford Focus

Steady-Speed Vehicle Dynamics

Steady-speed driving is such a simple case that many of the clarifications that apply to real-world driving dynamics do not apply. For example, because there are no inertia forces or variations in speed, wheel work is proportional to road-load at each speed, as shown in Figure 31. Similarly, average positive power is the road-load power, shown in Figure 32, which in this case, is also wheel work times velocity, something not true for transient speed traces. From these plots it is clear that neither wheel work nor tractive power directly explain fuel consumption at all speeds. They dominate at high speeds, but at low speeds, additional dynamic vehicle variables must be included, specifically those which reflect the efficiency of the vehicle.

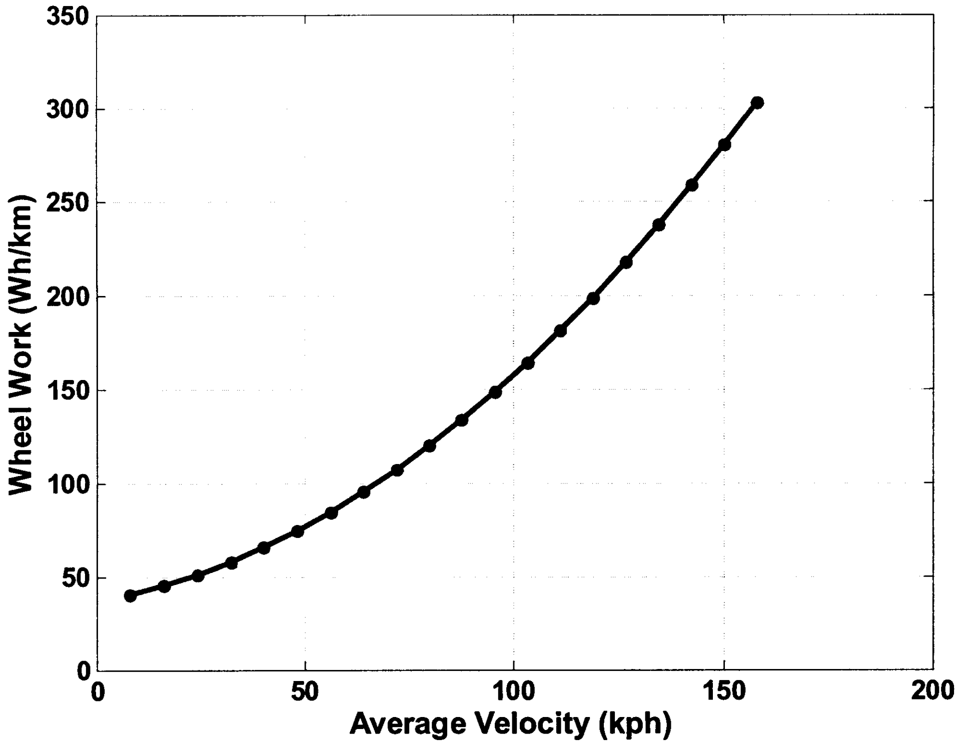

Figure 31: Wheel work versus cruise speed for stead-speed driving

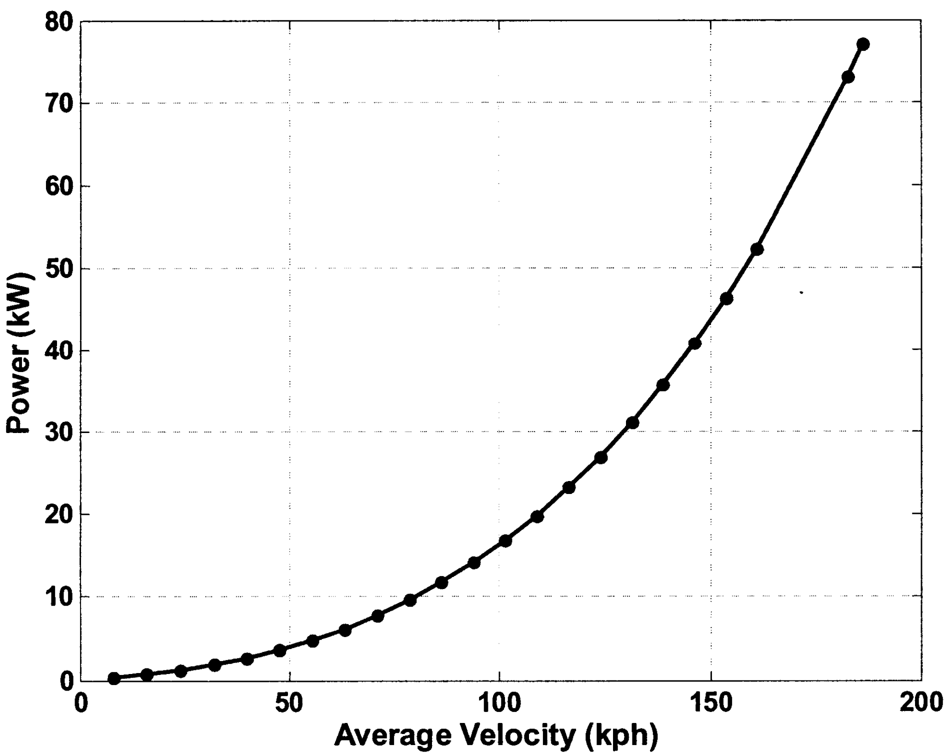

Figure 32: Average power versus cruise speed for stead-speed driving

Steady-Speed Vehicle Efficiency

Vehicle efficiency is a function of the vehicle design and the speed trace, and how they interact through the individual component efficiencies. The vehicle efficiency at each speed comes directly from the efficiencies of the main powertrain components. In a conventional, SI-ICE vehicle, these are the engine and transmission (which can be further separated into the gear box and torque converter/clutch), all of which are affected by the transmission design and shifting strategy. While European eco-driving programs focus on shift strategy as a significant source of fuel savings, because automatic vehicles represent over 94 percent of vehicles in the U.S. [EPA, 2009], the design and control strategy of the transmission itself is more important.

As shown in Figure 33, changes in cruise gear ratio align with the step changes in the fuel consumption curve. For speeds below 20 mph, the Ford Focus cruises in first gear. For speeds between 20 and 35 kph, the Focus cruises in second gear. Between 35 and 60 kph, it is in third gear; and for speeds above 60 kph, it cruises in fourth gear. This gear ratio affects both transmission and engine efficiency.

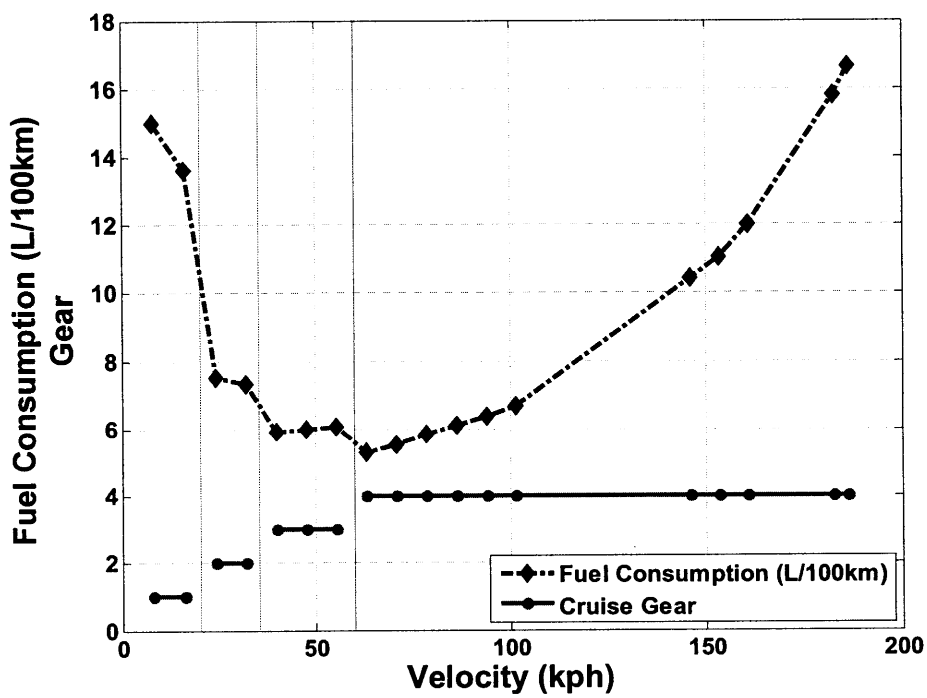

Figure 33: Fuel consumption and cruise gear of the Ford Focus during steady-speed driving versus cruise speed for a set of steady-speed traces. Vertical solid-black lines represent approximate changes in cruise gear

As shown in Figure 34 for the Ford Focus, gear box efficiency increases as the ratio between engine speed and vehicle speed increases, so, for steady-speed driving, with increasing vehicle speed. The slope between engine efficiency and speed changes with each change in gear ratio. Overall, engine efficiency increases roughly linearly with speed, up to 100 kph, with only slight changes in slope at 20 kph, 35 kph, and 60 kph. However, engine efficiency is better explained by tactive power, as shown in Figure 35.

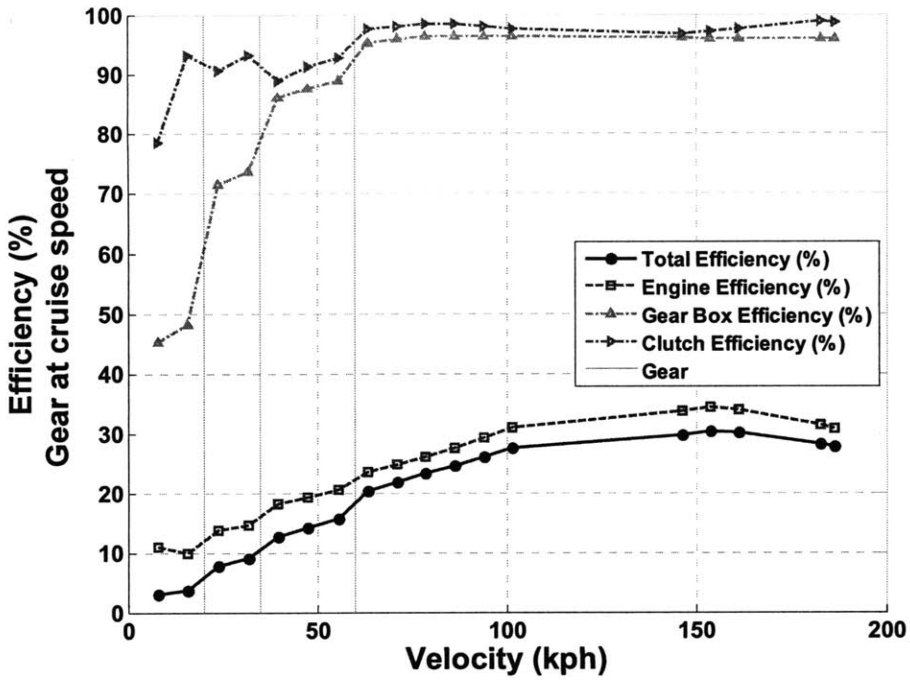

Figure 34: Component efficiencies of the Ford Focus during steady-speed driving

As shown in Figure 35, the engine gets more efficient at higher loads, up to a point. Initially, engine efficiency is logarithmically related to tractive power. Beyond this point efficiency remains high, but decreases slightly at very high loads. Because it is the least efficient powertrain component, the engine losses dominate overall vehicle efficiency, which is also shown in Figure 35 and has a similar relationship with tractive power.

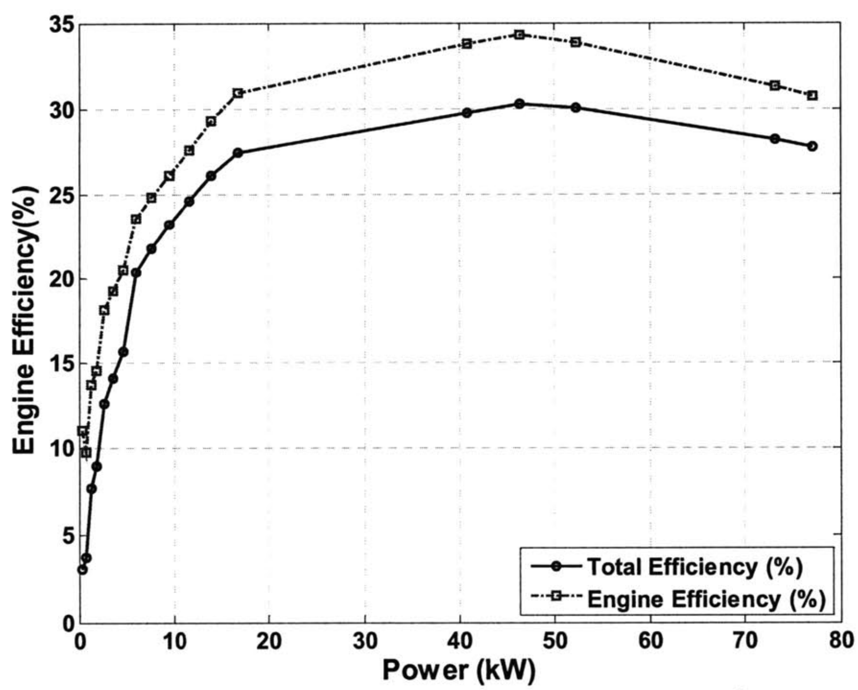

Figure 35: Engine and vehicle efficiency versus tractive power during steady-speed

Overall Effect

As shown in Figure 30 above, combining wheel work and vehicle efficiency explains the trend in steady-speed fuel consumption. Separating the wheel work and efficiency trends provides insight into the relationship between driving style and fuel consumption.

As shown above, for a conventional vehicle, at low speeds, both wheel work and efficiency are very low. As speed increases, wheel work increases slightly, but efficiency increases dramatically, causing overall fuel consumption to decrease. For moderate speeds, wheel work and efficiency increase roughly proportionally. For this range of speeds, steady-speed fuel consumption changes only slightly with speed. Then at higher speeds, efficiency remains constant or decreases while wheel work increases dramatically with speed. The effect is dramatic increases in fuel consumption. For speed ranges over which efficiency changes little, the vehicle is more sensitive, because wheel work continues to change.

Sensitivity to Vehicle Characteristics

Both optimal speed (for fuel consumption) and sensitivity to increasing speeds depend upon the vehicle characteristics. For example, a 1997 Toyota Celica achieves lowest fuel consumption at 25 mph, while a 1994 Oldsmobile Cutlass achieves optimal fuel consumption at 55 mph [West, McGill, Hodgson, Sluder, and Smith, 1997]. These differences can be explained by how different vehicle characteristics affect efficiency and wheel work. Figure 36 reconfirms the proportional relationship between wheel work divided by efficiency and fuel consumption for the Ford Focus, Honda Accord, Honda Civic, and Ford Explorer. However, the specific characteristics of the vehicles affect wheel work and efficiency differently.

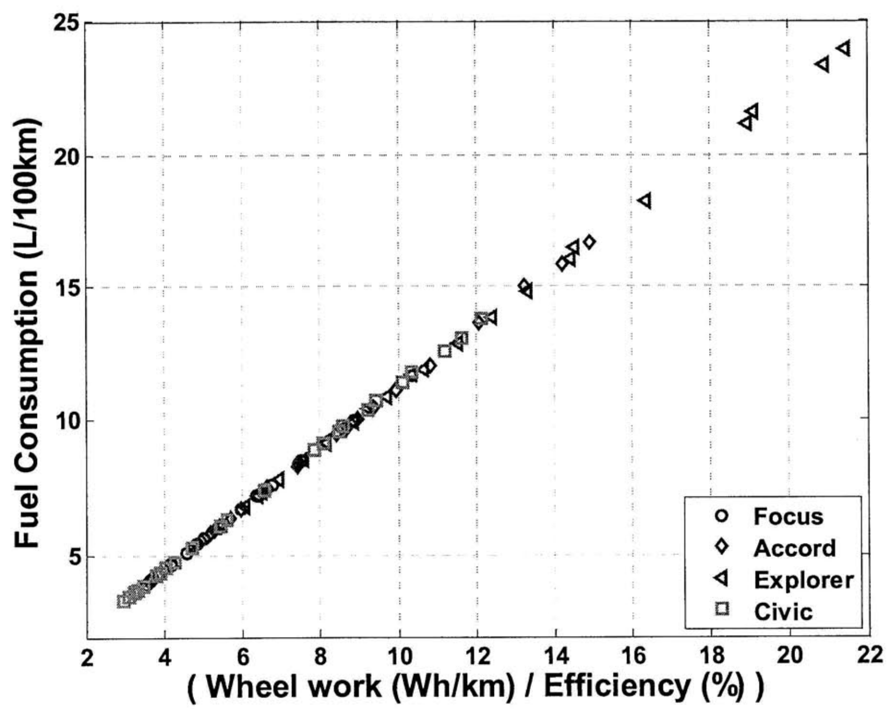

Figure 36: Fuel consumption versus wheel work divided by efficiency for steady-speed driving by the Focus, Accord, Explorer, and Civic

Wheel work

For any speed trace, a vehicle with higher wheel work but the same efficiency will have higher fuel consumption. For steady-speed, the wheel work is the road work. Because of this, the factor with the largest impact on wheel work is clearly aerodynamic drag (the C coastdown coefficient), which is a function of both frontal area and drag coefficient. Figure 37 compares steady-speed wheel work for the Ford Focus (C value of 0.37 $N \cdot s^2/m^2$) and the Ford Explorer (C value of 0.62 $N \cdot s^2/m^2$), showing the dramatic impact of aerodynamics on wheel work. Less aerodynamic vehicles have lower optimal speed. In addition, the fuel consumption of these vehicles is more sensitive to increases in vehicle speed.

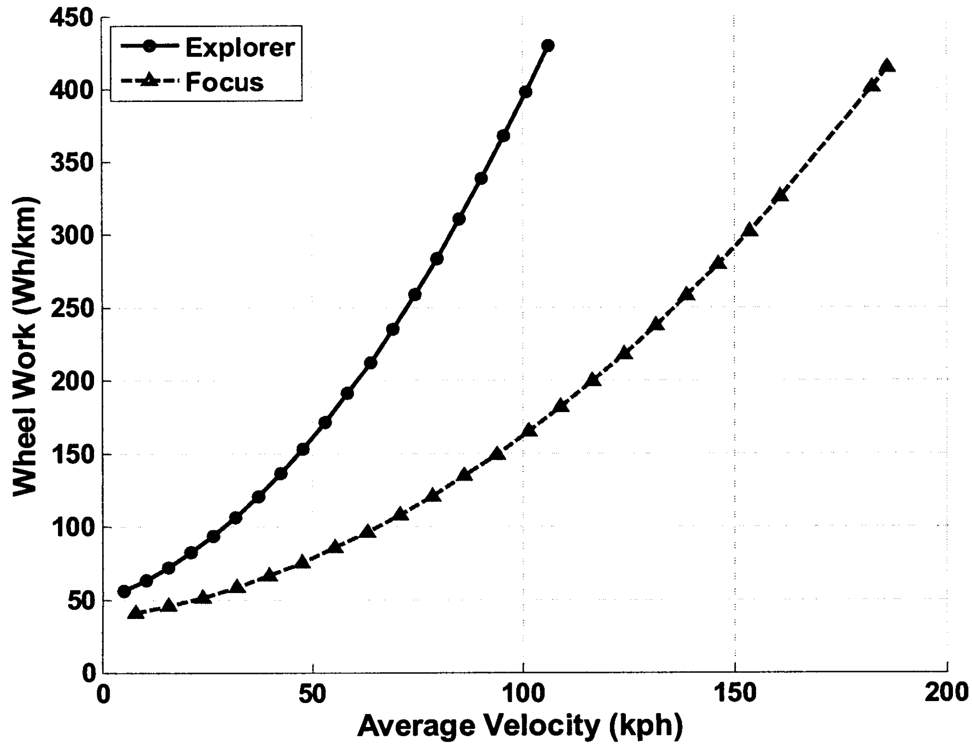

Figure 37: Steady-speed wheel work for the Ford Focus and Ford Explorer.

Vehicle Efficiency

Keeping vehicle technology constant, the primary factors affecting the overall efficiency are the power-to-weight ratio and the number and distribution of gear ratios. Design changes that increase average efficiency, but make efficiency more constant over a range of speeds increase the sensitivity of fuel consumption to aggressive driving. Vehicles with smaller engines and lower power-to-weight ratios are more sensitive to vehicle speed [Greene, 1981]. This can be explained by the engine efficiency. Consider two vehicles with similar coastdown coefficients and wheel work but with different power-to-weight ratios. Relative to engine power, the vehicle with lower power-to-weight ratio will have a higher proportional load on the engine, and thus higher average efficiency. Contrasting the Honda Civic (0.042 hp/lb) and the Ford Focus (0.048 hp/lb), both with 4-speed automatic transmissions, demonstrates this effect for steady-speed driving, as shown in Figure 38. Because of the inverse relationship between efficiency and fuel consumption, vehicles with lower power-to-weight ratio have lower overall fuel consumption. However, the sensitivity of fuel consumption is dependent on the change in efficiency, not the average efficiency. Accordingly, lower performance vehicles are more sensitive to higher velocities, at least until the engine efficiency of higher performance vehicles also begins to drop.

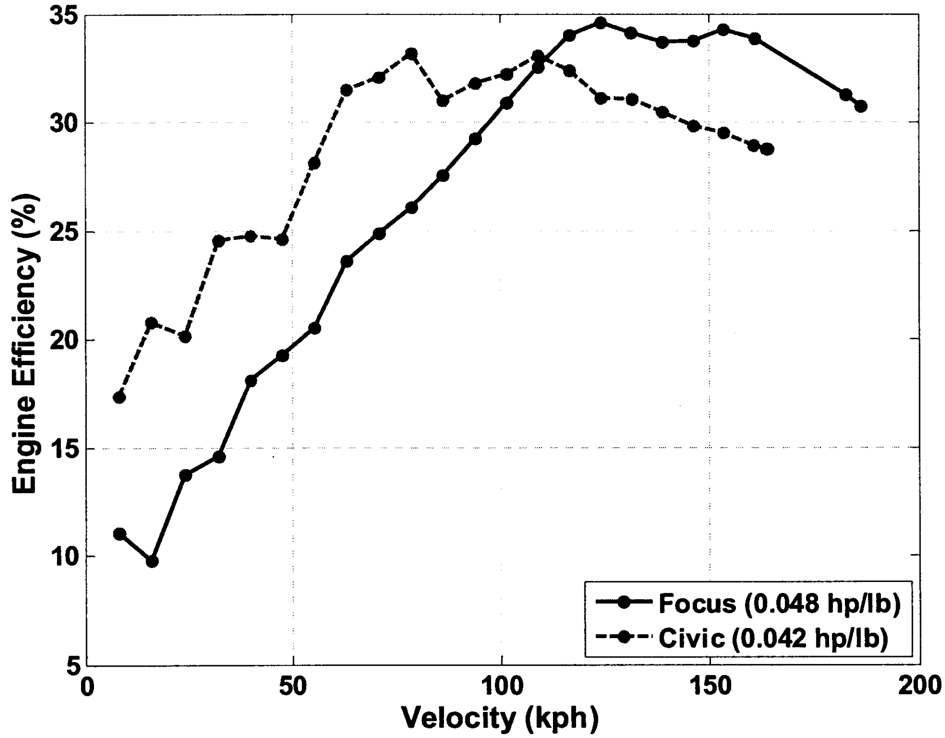

Figure 38: Engine efficiency versus vehicle speed for the Ford Focus and Honda Civic for steady-speed driving

As shown above, transmission design and shift strategy also affects efficiency. At each gear, engine speed and vehicle speed are proportional. Because of this, each change in gear ratio is accompanied by a change in the slope between engine efficiency and speed. The more gear changes over a specific speed range, the higher percentage of driving at which efficiency is high. Comparing the Ford Focus (Figure 39) to the Honda Accord (Figure 40), which has a 5-speed transmission and greater range of great ratios (Table 17), demonstrates this effect. By using more gears, over a wider range of speeds; the Accord is able to maximize engine efficiency over a larger range of vehicle speeds. From 0 to 150 kph, the Accord has an average engine efficiency of 27 percent, while the efficiency of the Focus engine is 25 percent, despite having higher peak efficiency. This increase in average efficiency is why European eco-driving programs focus on encouraging earlier up-shifting as one if the primary ways to save fuel. However, for sensitivity, the change in efficiency matters. Below 70 kph, the efficiency of the Accord increases more than that of the Focus. Above 70 kph, the efficiency of the Focus continues to increase, while that of the Accord remains relatively constant. As a result, the vehicle with fewer gears is more sensitive to lower speeds while the vehicle with more gears is more sensitive to higher speeds.

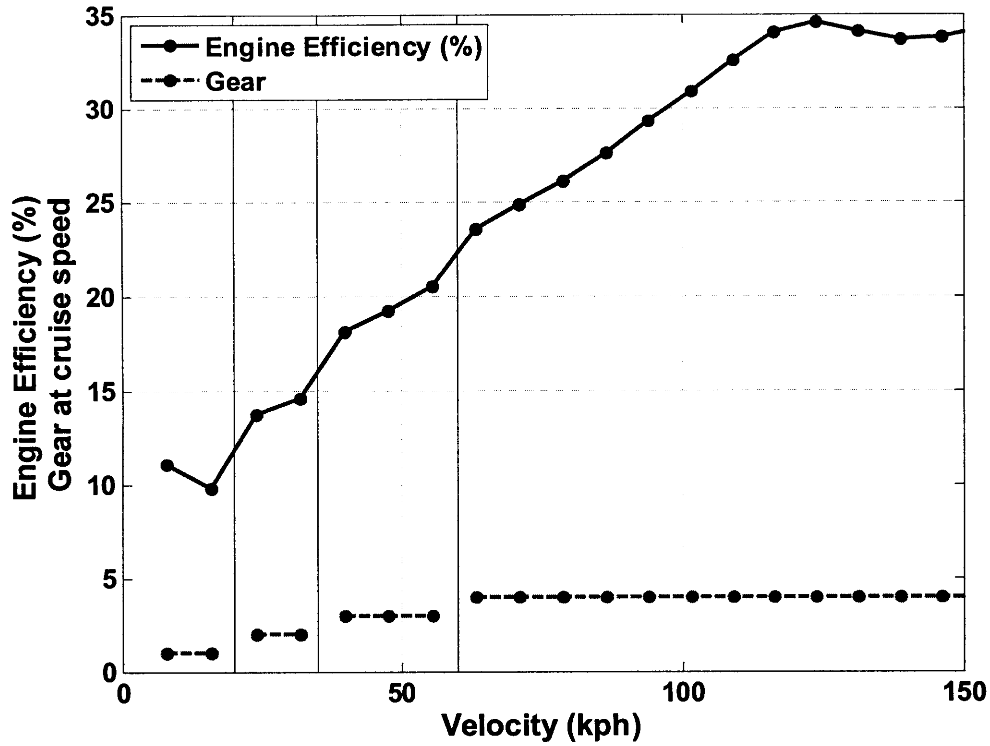

Figure 39: Engine speed versus velocity for the Focus during steady-speed driving

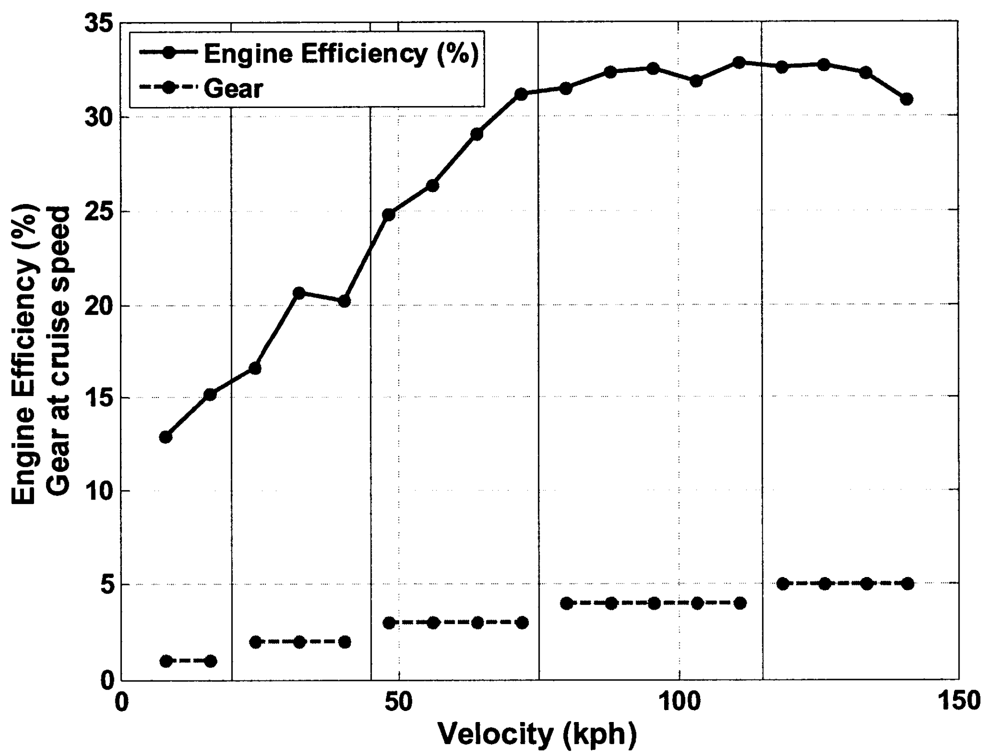

Figure 40: Engine speed versus velocity for the Accord during steady-speed driving

Table 17: Transmission ratios (gear ratio * final drive ratio) of the Focus and Accord

Gear	Accord	Focus
1st	11.8	10.6
2nd	6.7	5.7
3rd	4.4	3.8
4th	3.2	2.7
5th	2.5	NA

Resulting effects

The effects of aerodynamic drag, power-to-weight ratio, and number of gears can be summarized in Table 18 below. Reflecting the observations of Sharer, Leydier, and Rousseau [2007], vehicles with higher, but more constant efficiency across a wide range of speeds, tend to be much more sensitive to changes in speed. On the other hand, vehicles with lower, but more variable efficiency are less sensitive. This is because when efficiency does change, it increases with wheel work; and when efficiency is constant, wheel work continues to increase. Accordingly, for conventional vehicles, design changes that increase vehicle efficiency and decrease overall fuel consumption tend to increase sensitivity to high speeds. Design changes that increase the sensitivity of wheel work to speed (primarily, through aerodynamic drag) increase both fuel consumption and sensitivity to high speeds.

Table 18: Impact on fuel consumption

	Base Fuel Consumption	Sensitivity to Lower Speeds	Sensitivity to Higher Speeds
Aerodynamic Drag	↑	↑	↑
Power-to-weight	↑	↑	↓
Number of Gears	↓	↓	↑

Comparing the steady-speed fuel consumption of the Focus to the Explorer, Civic, and Accord, Figure 41, illustrates these effects. Because the role of the individual factors can not be separated out, this figure is only illustrative of the overall affects. The results are summarized in Table 19. Taking optimal speed as reference, the fuel consumption of the Ford Focus increases the least with increasing speed, followed by the Accord, then the Explorer. But it is the Civic, with its low aerodynamics, 4-speed transmission, and low power-to-weight ratio that is most sensitive to increases in speed. With decreasing speed, all four vehicles experience a similar proportional increase in fuel consumption. Although – because of a higher base consumption – the Explorer experiences a larger absolute increase in fuel consumption.

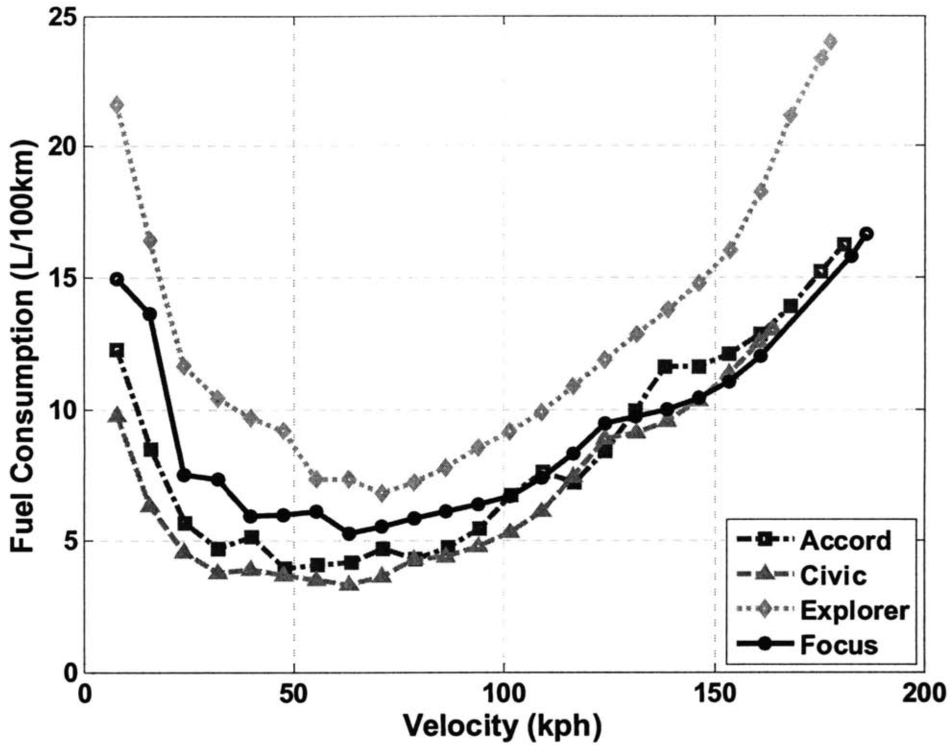

Figure 41: Fuel consumption versus cruise speed for steady-speed driving by the Ford Focus, Honda Accord, Ford Explorer, and Honda Civic

Table 19: Simulation-based steady-speed fuel consumption of Civic, Focus, Accord, and Explorer

	Optimal Speed Range (kph)*	Optimal Fuel Cons. (L/100km)	Fuel Consumption at			Sensitivity of Fuel Cons. to Speed (L/hr)	Fuel Saving of slowing from 75 to 65 mph
			55 mph	65 mph	75 mph		
Civic	55-63	3.3	4.5	5.6	30.9	11.8	31%
Focus	63-70	5.2	6.2	7.0	21.3	8.7	21%
Accord	48-63	4.0	4.9	7.2	7.7	9.2	8%
Explorer	65-75	6.8	8.1	9.5	16.7	10.7	17%

* Optimal speed range is within 5% of lowest (optimal) fuel consumption

These overall trends are confirmed by the literature on steady-speed driving, with varying sensitivities to speed. West et al. [1997] found that slowing from 70 to 65 mph reduced the fuel consumption of a typical vehicle by 8 percent. Recent testing by Consumer Reports [Barth 2009], summarized in Table 20, found comparable percent fuel savings from highway speed reductions (assessed for a reduction from 75 to 65 mph). Relative to the PSAT simulations, sensitivity (increase in L/km per increase in kph) values are similar. However, the Consumer Reports vehicles do no exhibit the range of percent fuel savings. Of the Consumer Reports vehicles, sensitivity to speed increased primarily with vehicle size, from the subcompact Toyota Yaris to the Mercury Mountaineer. However, as above, it is difficult to separate the effects of weight, power-to-weight ratio, and aerodynamic resistance since none are controlled.

Table 20: Steady-speed fuel consumption from track testing by Consumer Reports [Barth 2009]

	Vehicle Class and Engine	HP/Lb	Fuel Consumption			Sensitivity of Fuel Cons. to Speed (L/hr)	Fuel Saving of slowing from 75 to 65 mph
			55 mph	65 mph	75 mph		
Toyota Yaris	Subcompact 1.5-liter 4-cyl.	0.041	5.5	6.2	6.9	4.3	10%
Acura TSX	Compact 2.4-liter 4-cyl.	0.054	5.9	6.6	7.7	5.5	14%
Toyota Camry	Mid-Size 2.5-liter 4-cyl.	0.047	5.8	6.7	7.9	6.4	15%
Toyota RAV4	Small SUV 2.5 liter 4-cyl.	0.049	6.8	8.0	9.1	7.1	12%
Lexus RX350	Midsize SUV 3.5-liter V6	0.065	7.6	8.6	10.2	8.1	16%
Mercury Mountaineer	Large SUV 4.6-liter V8	0.044	9.9	11.1	13.2	10.4	16%

5.2 Transient Speed Traces

Building from the understanding of how changes in wheel work and efficiency affect fuel consumption, this section looks at more realistic, transient speed traces. It examines the effects of velocity and acceleration separately.

Effect of Velocity on Fuel Consumption

As shown in Figure 42, when the average speed of a driving pattern changes, the resulting fuel consumption follows the same u-shape observed for steady-speed driving. Three standard drive cycles and four real-world driving patterns were modified to scale velocities without affecting acceleration rates. The process for generating these cycles is explained in Chapter 3. Each point in the figure represents the average velocity and fuel consumption for an entire speed trace. For each of the seven speed traces, the minimum fuel consumption occurs at moderate speed, between 30 and 65 kph. From this "optimal speed," fuel consumption increases with both increasing and decreasing average speed. This shape can be explained by looking at the wheel work (Figure 43) and efficiency (Figure 44) plots for the same set of speed traces. At low speeds, both wheel work and efficiency increase with increasing speed; however, efficiency increases much more than wheel work, causing a decrease in fuel consumption. At moderate speeds, wheel work and efficiency increases roughly proportionally with increasing speed. At high speeds, wheel work increases dramatically while efficiency remains constant, then decreases; causing an increase in fuel consumption with speed.

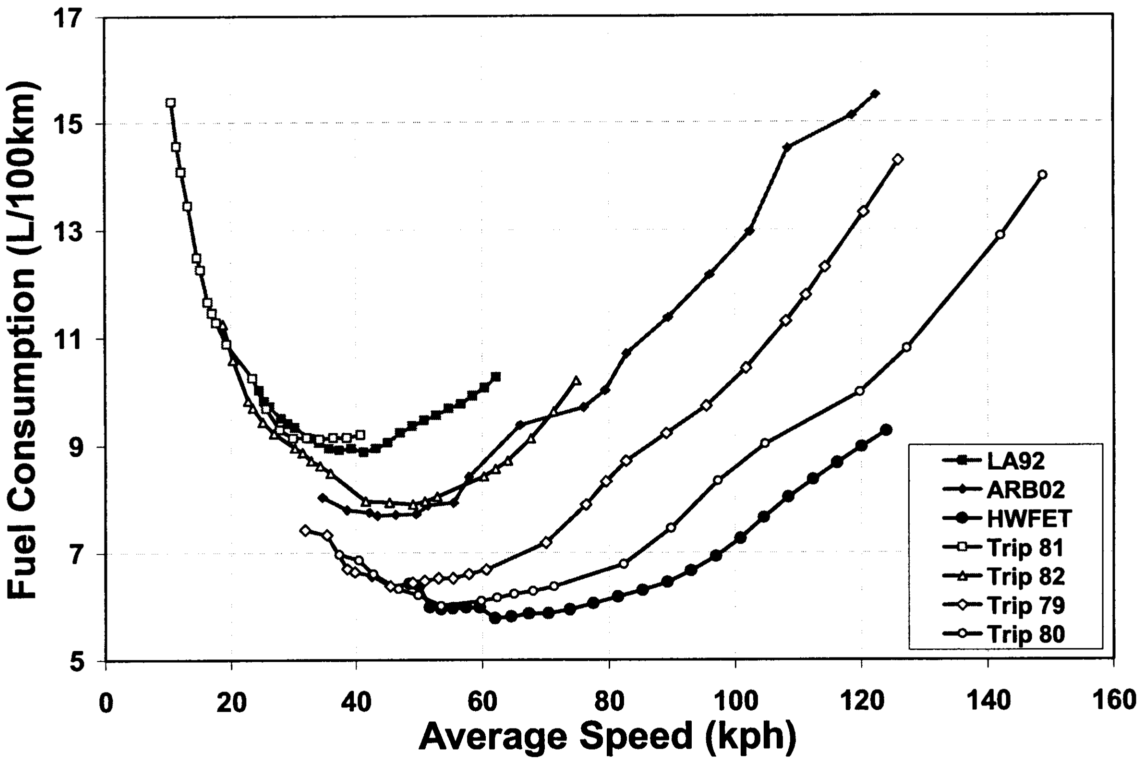

Figure 42: Fuel consumption versus average velocity for velocity-modified speed traces

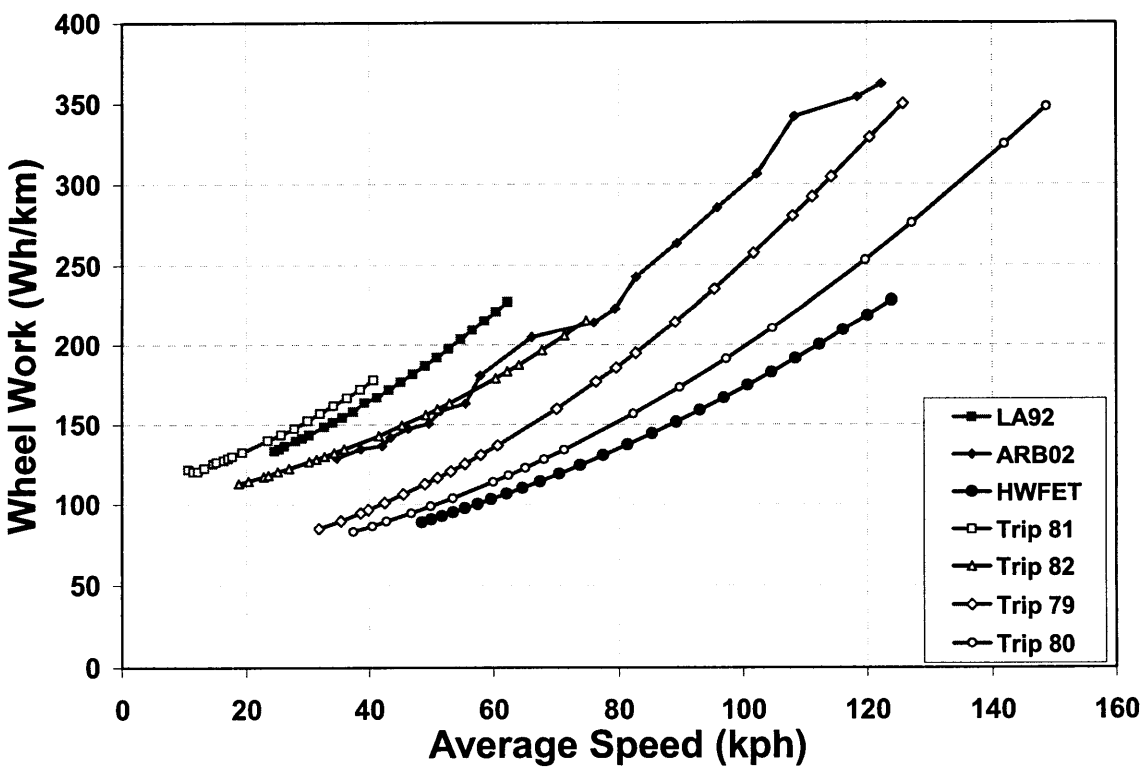

Figure 43: Wheel work versus average velocity for velocity-modified speed traces

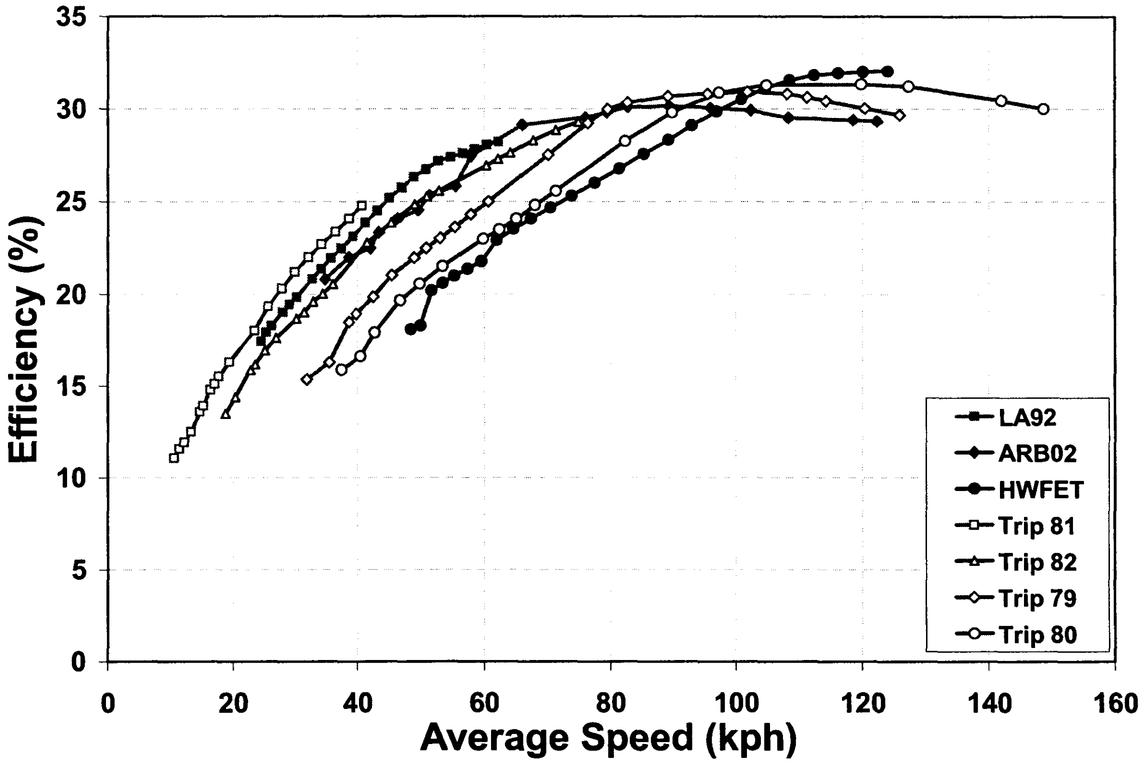

Figure 44: Efficiency versus average velocity for velocity-modified speed traces

While the overall trend is the same for all seven sets of speed traces, the rate at which fuel consumption, wheel work, and efficiency change with speed varies from speed trace to speed trace. This is due to differences in the overall dynamics. Although acceleration values remain the same, they occur at higher or lower speed and for a longer or shorter period of time, impacting the result. For example, the HWFET average positive acceleration is only 0.16 m/s^2 while the LA92 average acceleration is 0.56 m/s^2.

Effect of Acceleration on Fuel Consumption

In a 1980 EPA technical report, Jones showed that fuel consumption increased roughly linearly with acceleration under controlled, constant acceleration, test track conditions [Jones, 1980]. PSAT simulation results for the same seven speed traces as above verify this effect for realistic, transient speed traces, as shown in Figure 45. The process for generating these cycles is explained in Chapter 3. With all increases in average acceleration, fuel consumption increases. The "optimal acceleration" is as low as possible, with "ideal fuel consumption" at steady-speed driving. As shown in Figure 46 (wheel work) and Figure 47 (efficiency), accelerations cause both wheel work and efficiency to increase, but cause much greater increases in wheel work than in efficiency. As with increasing velocities, the magnitude of the increase in fuel consumption varies slightly from cycle to cycle.

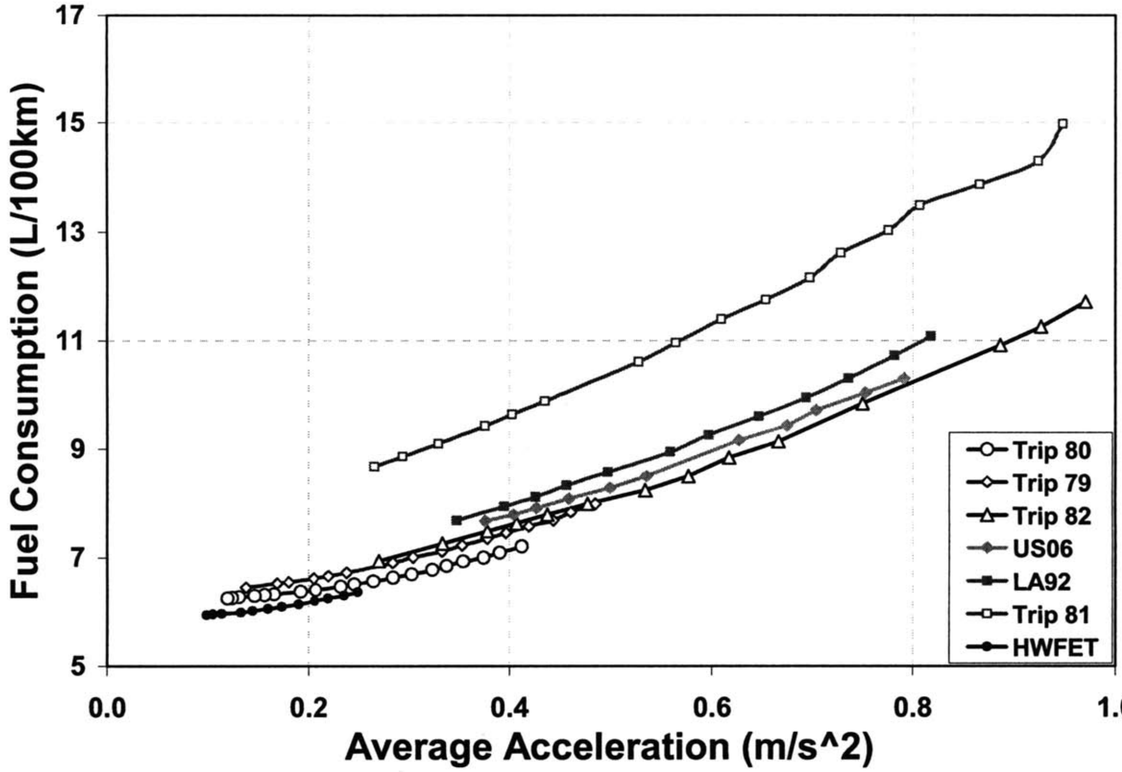

Figure 45: Fuel consumption versus average acceleration for acceleration-modified traces

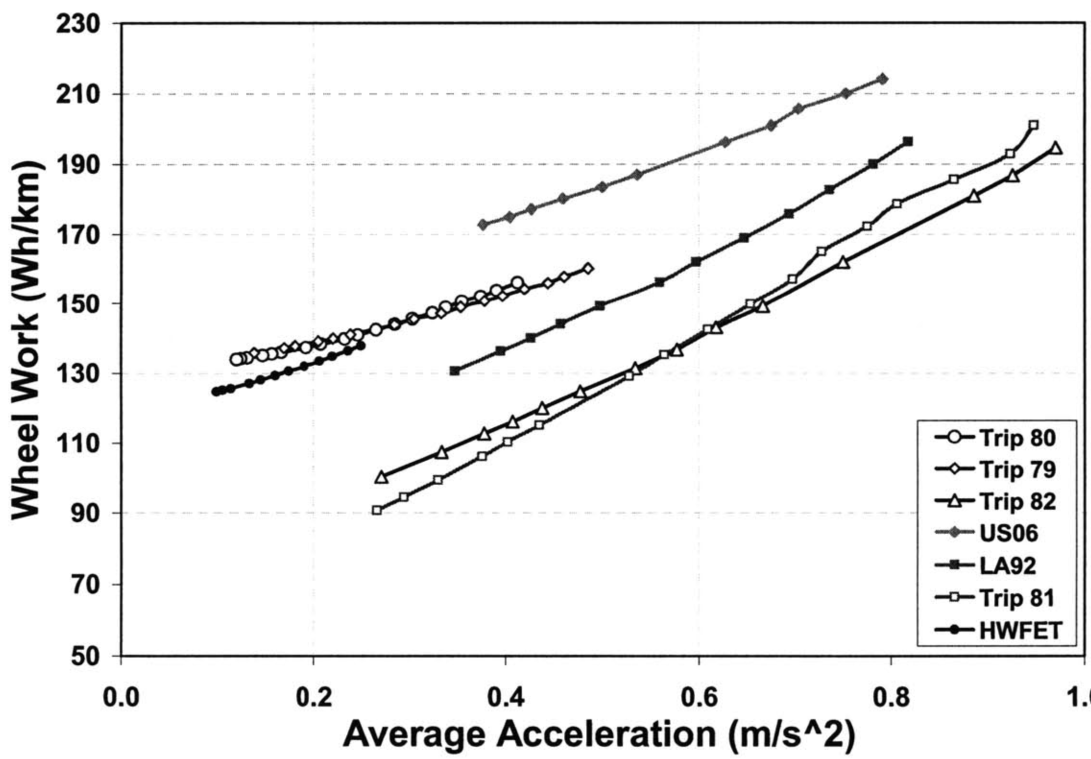

Figure 46: Wheel work versus average acceleration for acceleration-modified traces

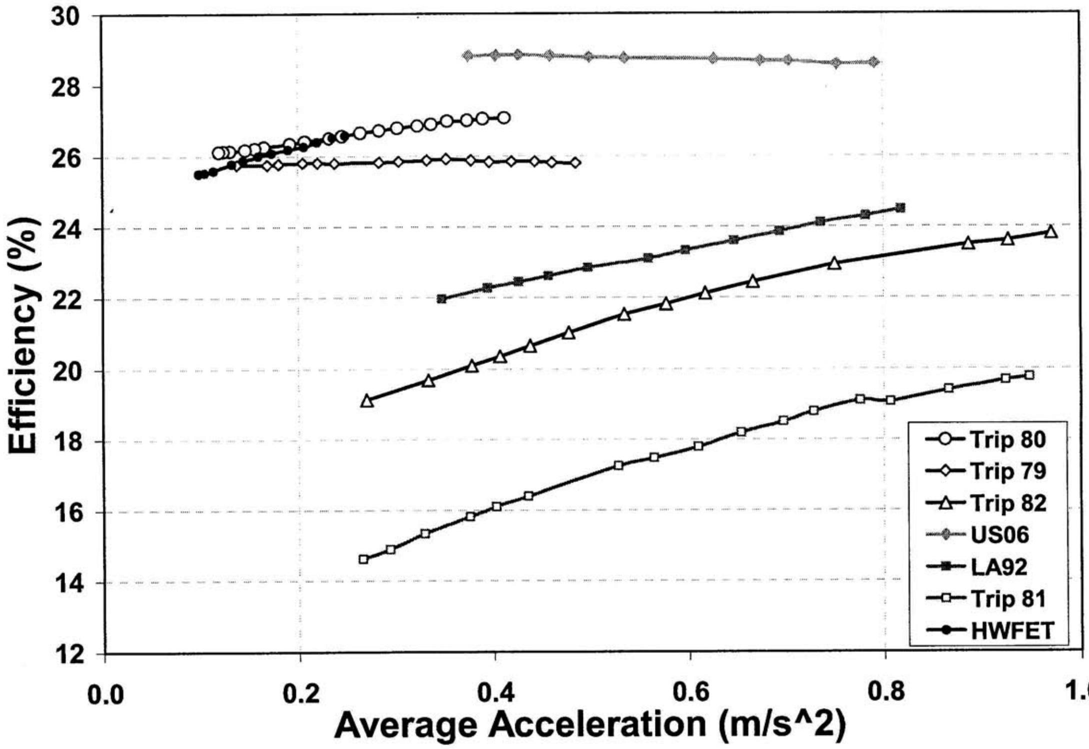

Figure 47: Vehicle efficiency versus average acceleration for acceleration-modified traces

5.3 Overall Fuel Consumption Trends

In the complete set of over 1,100 speed traces described in Chapter 3, the effects of various velocities and accelerations are merged, as shown in Figure 48 (fuel consumption versus average velocity) and Figure 49 (fuel consumption versus average acceleration). Creating a 3d plot with acceleration, velocity, and fuel consumption does nothing to illuminate the relationship between driving style and fuel consumption. A different approach is needed, one that directly reflects how a speed trace affects wheel work and efficiency. As an intermediate step, tractive power serves as an indicator of efficiency.

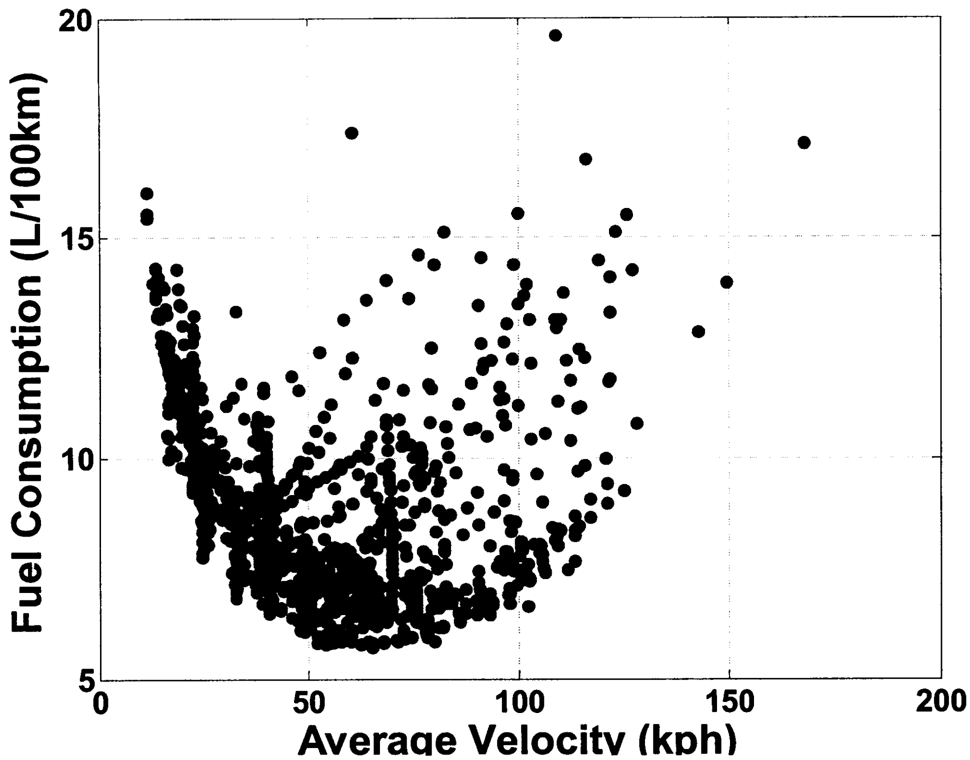

Figure 48: Ford Focus fuel consumption versus average velocity for the complete set of speed traces

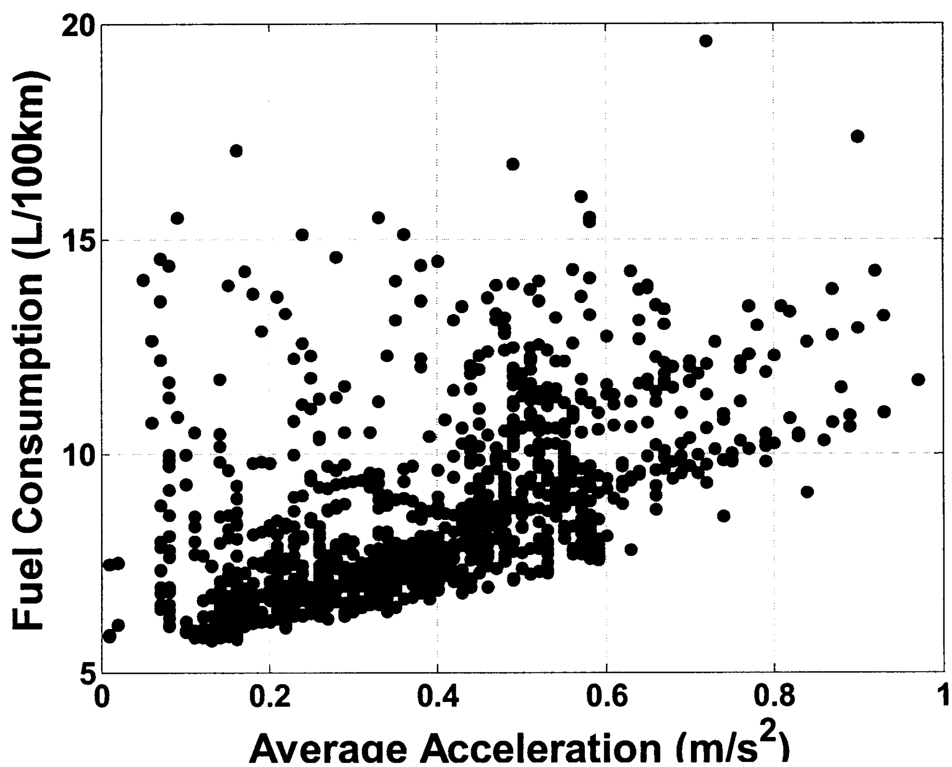

Figure 49: Ford Focus fuel consumption versus average positive acceleration for the complete set of speed traces

Average Power as an Indicator of Vehicle Efficiency

The relationship between tractive power and vehicle efficiency observed for steady-speed driving holds true for the accumulated transient speed traces, although with variability at moderate and high power, as shown in Figure 50. In general, efficiency is logarithmically related to average tractive power up to some power (roughly 20 kW for the Ford Focus). Beyond this point (up to at least 70 kW) efficiency is roughly constant. The longer the drive cycle, the tighter this pattern becomes.

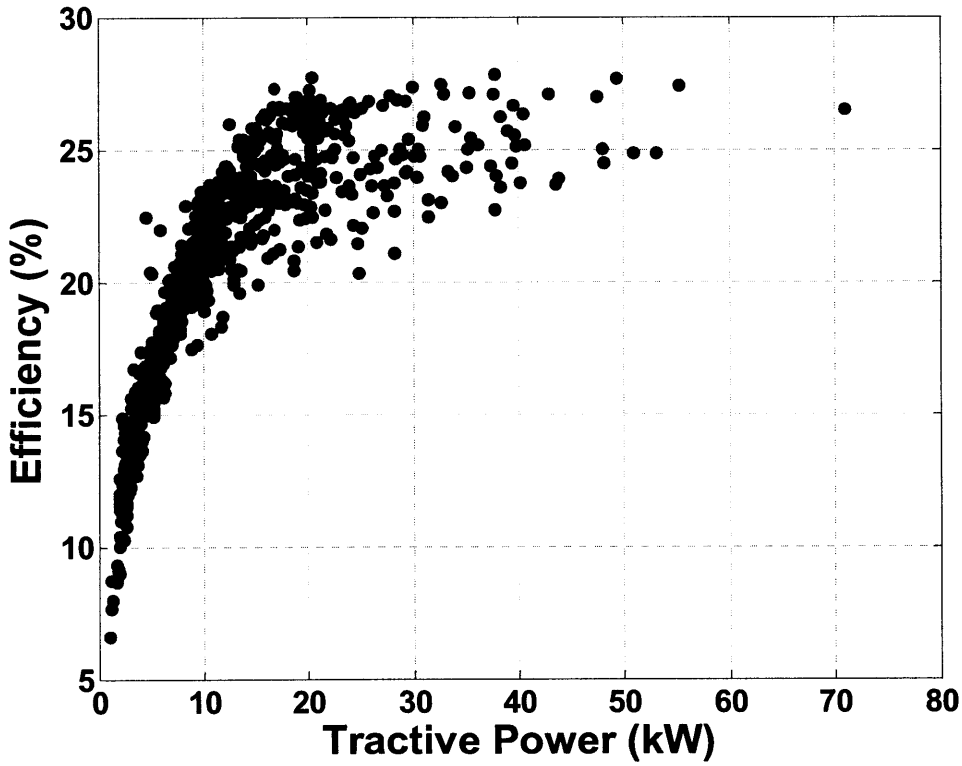

Figure 50: Vehicle efficiency versus tractive power for the complete set of speed traces

Interpreted as Accelerations and Velocities

To put this relationship back in terms of acceleration and velocity, Figure 51 shows the *instantaneous* tractive power of the Ford Focus for a range of positive accelerations and velocities, bounded by the maximum engine power. The relationship between tractive power and efficiency is based on averages, not instantaneous values, so this figure is only illustrative, but helps illuminate how fuel consumption is affected by acceleration and velocity. In the low speed and low acceleration region power is below 20 kW: efficiency increases dramatically with power, as shown in Figure 50. Above 20 kW (the solid black curve), efficiency is relatively constant with power. A similar plot of wheel work (Figure 52) demonstrates the dependence of wheel work on velocity and, primarily, on acceleration.

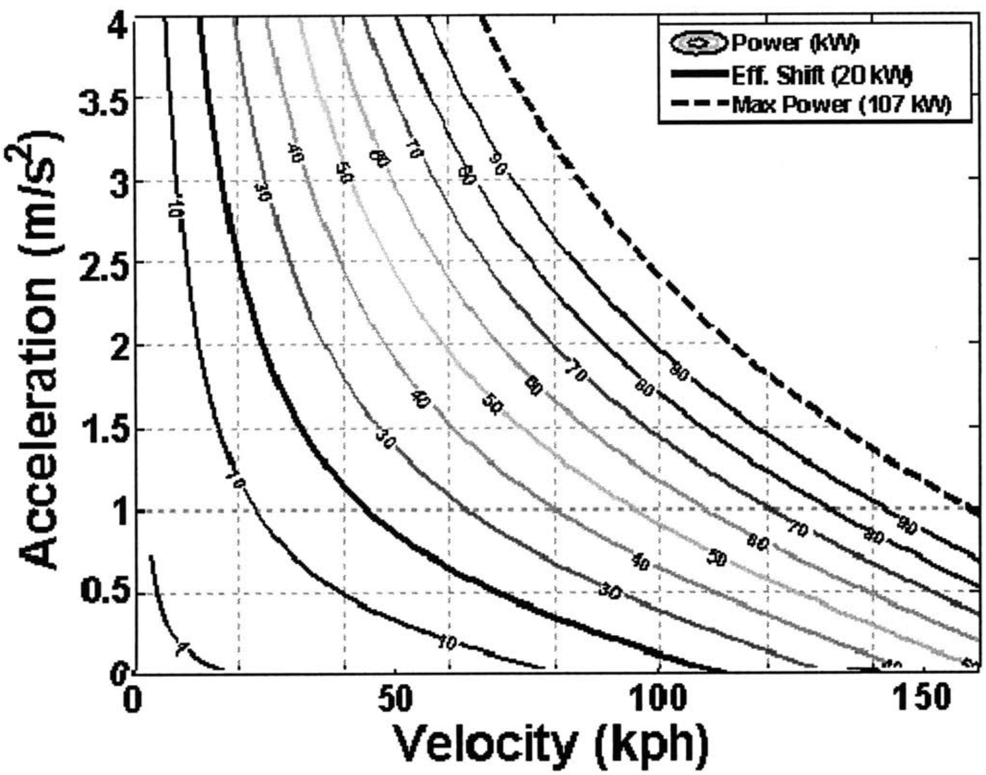

Figure 51: Instantaneous power over a range of accelerations and velocities, bounded by the maximum engine power of the Ford Focus

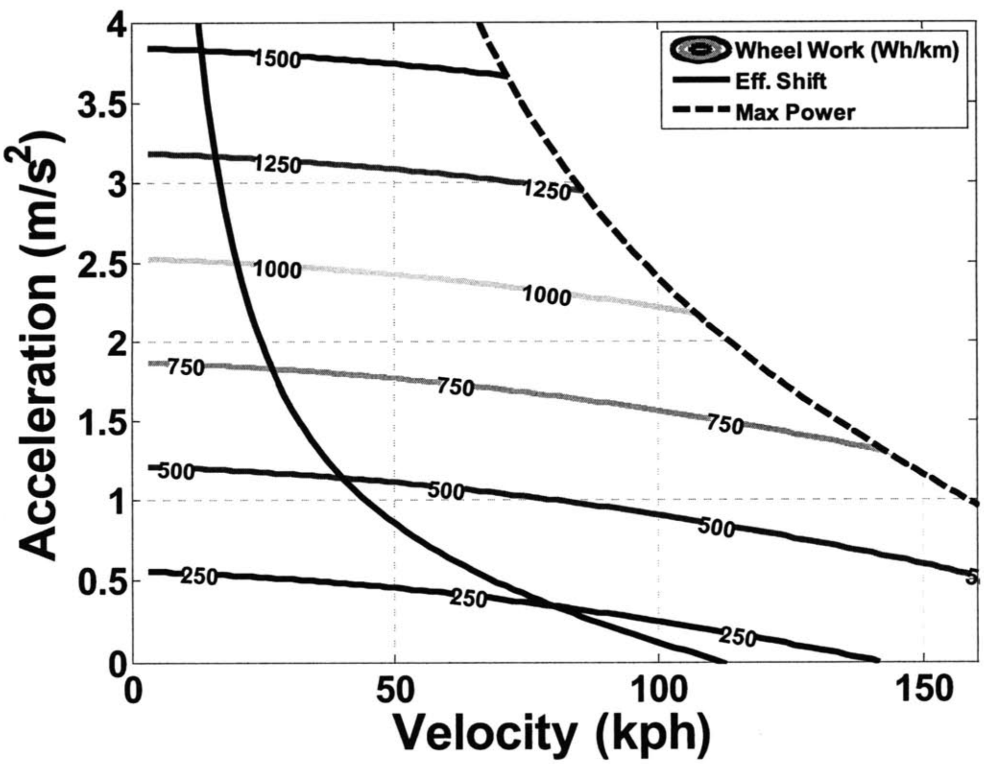

Figure 52: Instantaneous wheel work over a range of accelerations and velocities, bounded by the maximum engine power of the Ford Focus

By combining these two plots, we observe that:

1. At low speeds (below 20 mph): with increasing speed, efficiency increases more than wheel work; and with increasing acceleration, wheel work increases more than efficiency.
2. At moderate speeds (20 to 45 mph): with increasing speed, efficiency and wheel work increase proportionally; and with increasing acceleration, wheel work increase more than efficiency
3. At high speeds (above 45 mph): with both increasing speed and increasing acceleration, wheel work increases dramatically, but efficiency changes little

Wheel work, Velocity, and Fuel Consumption

Exploring average velocity and wheel work in more detail shows that, together, they form a map with regions of consistent fuel consumption trends, shown in Figure 53. The lower boundary of this map (the solid red line) is the steady-speed wheel work. Fuel consumption increases, by differing amounts, as both average speed and wheel work move away from the minimum fuel consumption (steady-speed driving at 64 kph). In area 1, low speeds, fuel consumption is most dependent on vehicle speed, increasing with decreasing speed and with increasing accelerations. In area 2, moderate speeds, fuel consumption is most insensitive to changes in velocity and wheel work. It increases primarily with wheel work, but, to a lesser amount, with both higher and lower velocities. Area 3, high speeds, fuel consumption increases with both speeds and accelerations. Note that the contour lines are smoothest when the density of data points (drive cycles) is highest. Building from this understanding of vehicle dynamics, the following chapter defines a metric to quantify aggressiveness.

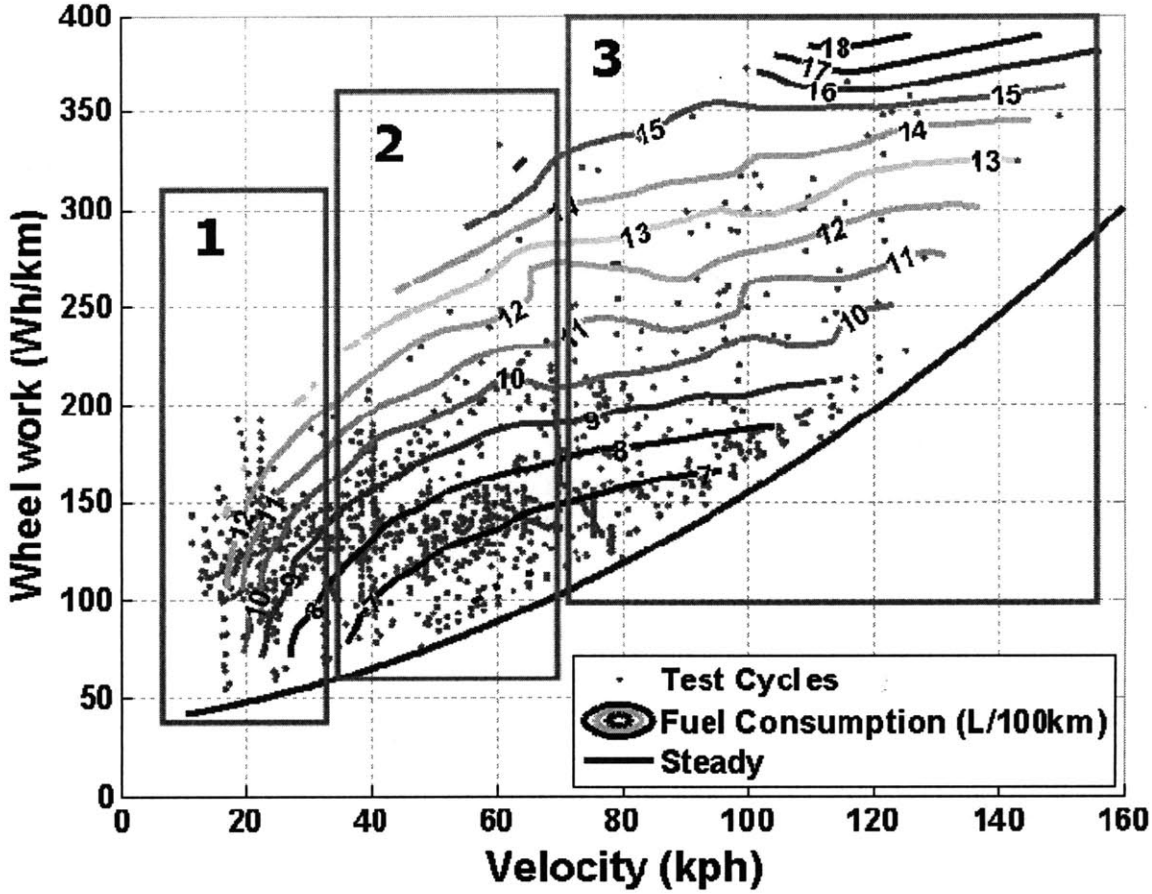

Figure 53: Fuel consumption for a range of wheel work and average velocities, with lines of constant fuel consumption and the 1,100 test cycles

6 Characterizing Driving Aggressiveness

Building from the discussion of vehicle and driving dynamics in Chapter 4 and vehicle efficiency and fuel consumption in Chapter 5, this chapter defines and proposes aggressiveness factors that were developed specifically to meet four criteria:

1. Can be calculated based on only driving pattern and vehicle characteristics,
2. Reflect driving style,
3. Correlate with fuel consumption, and
4. Are normalized by vehicle mass.

These criteria were selected to maximize the utility of the aggressiveness factors in answering the research questions. The aggressiveness factors do not rely on fuel consumption or fuel flow information since those values are influenced by variables other than driving style. However, to be useful for studying impacts on fuel consumption, the aggressiveness factors must correlate directly with fuel consumption. To illuminate which driving behaviors have the greatest impact on fuel consumption, the aggressiveness factors must quantify driving behaviors based on how they impact fuel consumption. Recognizing the significance of mass in fuel consumption, in order to be more comparable across vehicles the aggressiveness factors should be mass-normalized.

The result is a method for quantifying and comparing drive cycles, driving patterns, and drivers. In developing these aggressiveness factors, a range of options were considered. However, as shown in the previous chapters, average speed and wheel work, together, can illuminate and predict fuel consumption. The aggressiveness factors rely on these parameters. In addition, because fuel consumption differs at different speed bands, separate aggressiveness factors were defined for each of three separate speed bands: below 20 mph (32 kph), between 20 and 45 mph (32 and 72 kph), and above 45 mph (72 kph). The separating speeds (20 and 45 mph) were selected by first choosing initial values based on the trends identified in Chapter 5, then fine-tuning them to optimize the fit of the three aggressiveness factors. Speed traces are sorted into these speed bands based on average speed. For simplicity, they have been given the names of "neighborhood," "city," and "highway" driving.

This chapter defines and discusses each of the three aggressiveness factors, starting with city driving. Finally, it explores how the aggressiveness factors can be used.

6.1 Aggressiveness Factor for City Driving

City driving is taken as any driving with average speed between 20 and 45 mph (32 and 72 kph). The aggressiveness factor for driving in this range is the most intuitive and straightforward. As shown in Figure 54 for the 590 speed traces that fall within the city speed band (each point representing an entire trace), the relationship between wheel work and fuel consumption is roughly linear, but with great variation. Removing the steady-speed wheel work from a given drive cycle, yields "acceleration wheel work," which has a much tighter fit with fuel consumption, as shown in Figure 55.

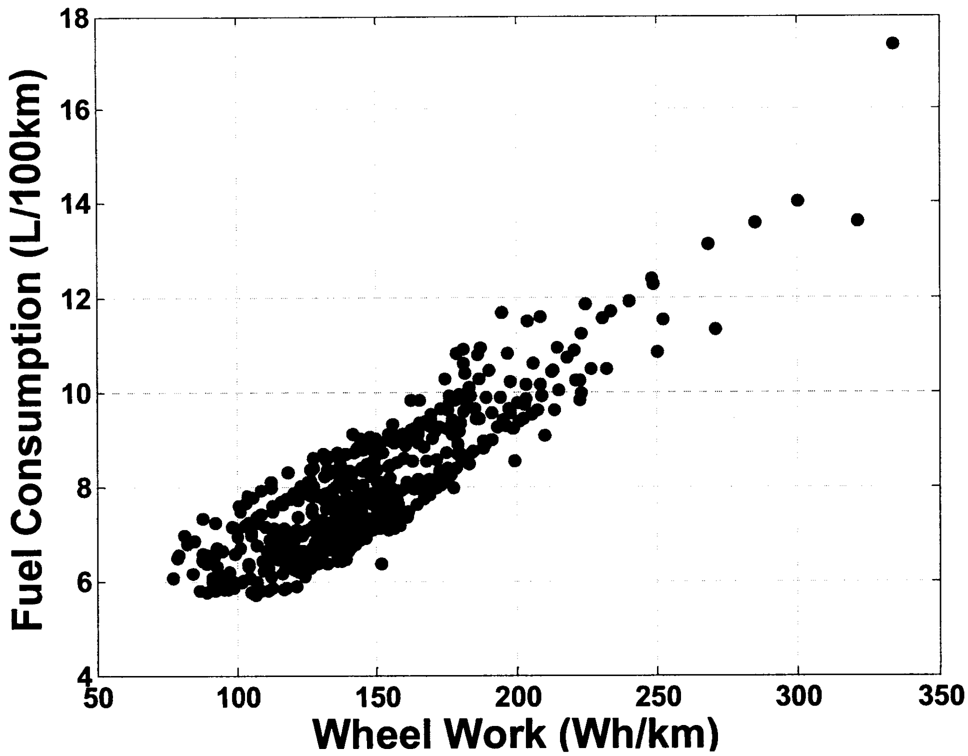

Figure 54: Fuel consumption versus wheel work for speed traces with average velocity between 20 and 45 mph (32 and 72 kph)

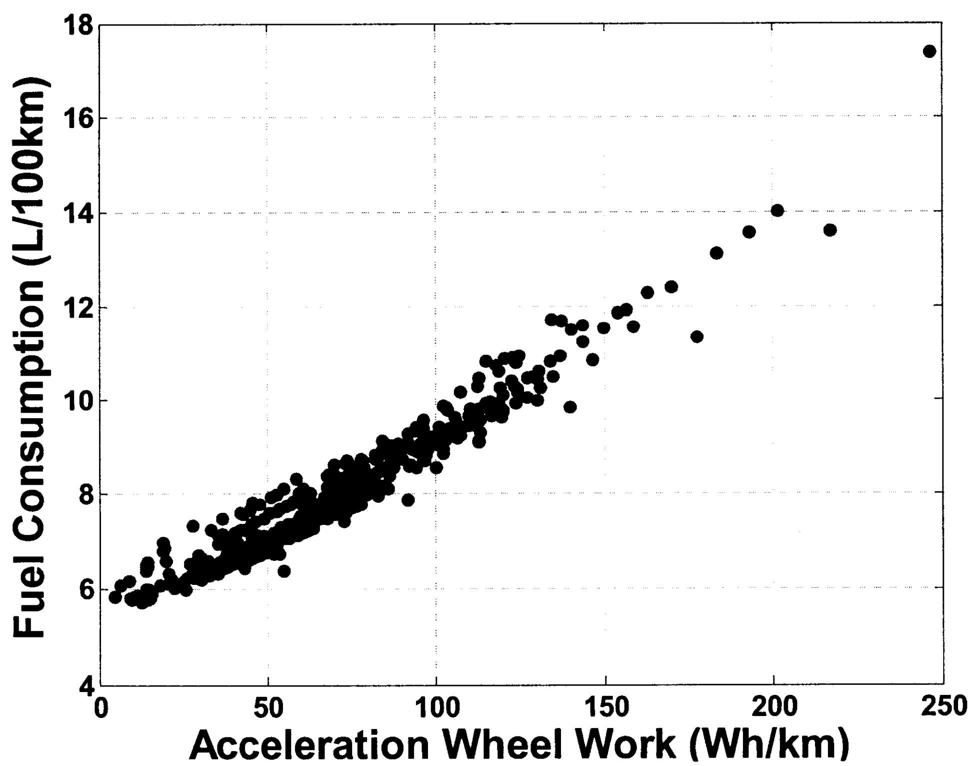

Figure 55: Fuel consumption versus acceleration wheel work for speed traces with velocity speed between 20 and 45 mph (32 and 72 kph)

Finally, the acceleration wheel work is normalized by vehicle mass, giving units of acceleration. However, although aggressiveness factors have units of accelerations, they are not actual accelerations and are not proportional to any acceleration values. The final equation for city aggressiveness factor is expressed in words as:

$$Aggressiveness\ factor = \frac{Wheel\ Work - Steady\ Speed\ Wheel\ Work\ at\ Average\ Speed}{Mass} \quad (21)$$

And in variables as:

$$AF_{City} = \left(\frac{1}{M}\right)\left[\left(\frac{\int \left(Av + Bv^2 + Cv^3 + Mav\right)^{+} dt}{\int v dt}\right) - \left(Roadlaod(\bar{v})\right)\right] \quad (22)$$

As shown in Figure 56, this factor is linearly related to fuel consumption. For the Ford Focus, every 1 m/s^2 increase in city aggressiveness causes an increase of 4.4 L/100km in fuel consumption. The norm of the residuals for this fit is 8.4.

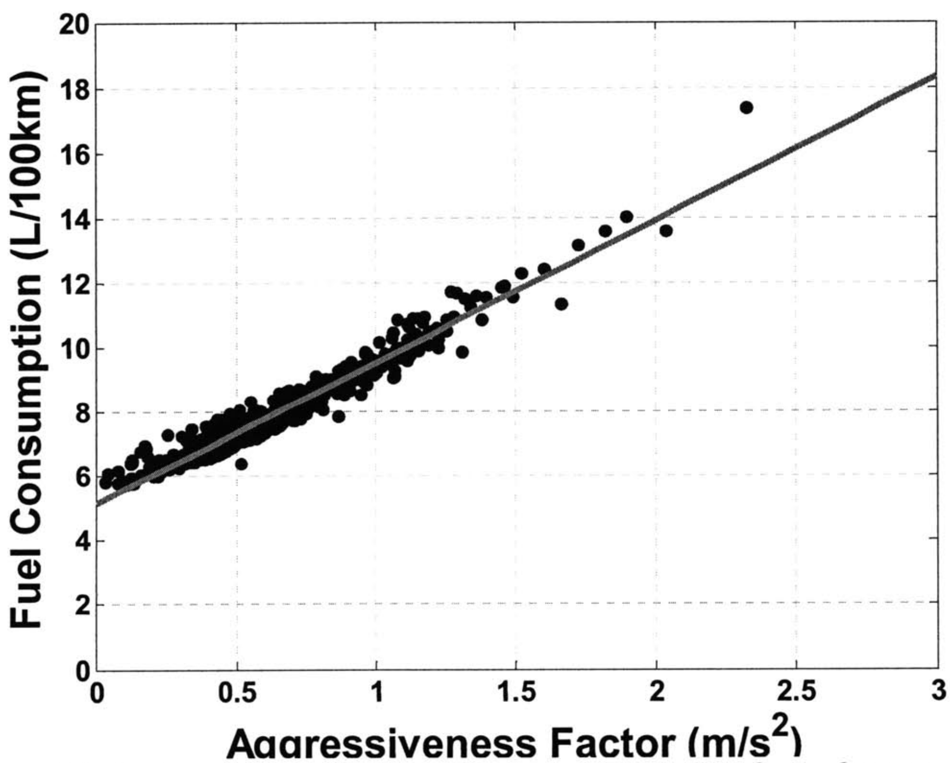

Figure 56: Fuel consumption versus the city aggressiveness factor for speed traces with average velocity between 20 and 45 mph (32 and 72 kph)

Interpretation as Accelerations and Velocities

In addition to providing a tool to quantitatively compare driving patterns, each of the three aggressiveness factors provides insight into the driving behaviors that most impact fuel consumption in that speed band. For city driving, this is clearly accelerations. Figure 57 shows instantaneous aggressiveness factors for the Ford Focus over a range of accelerations and city velocities. This figure is for illustrative purposes only to help interpret city driving. It is not a look-up table of aggressiveness factors, which are based on average driving, not instantaneous driving. The city aggressiveness factor is unaffected by changes in velocity.

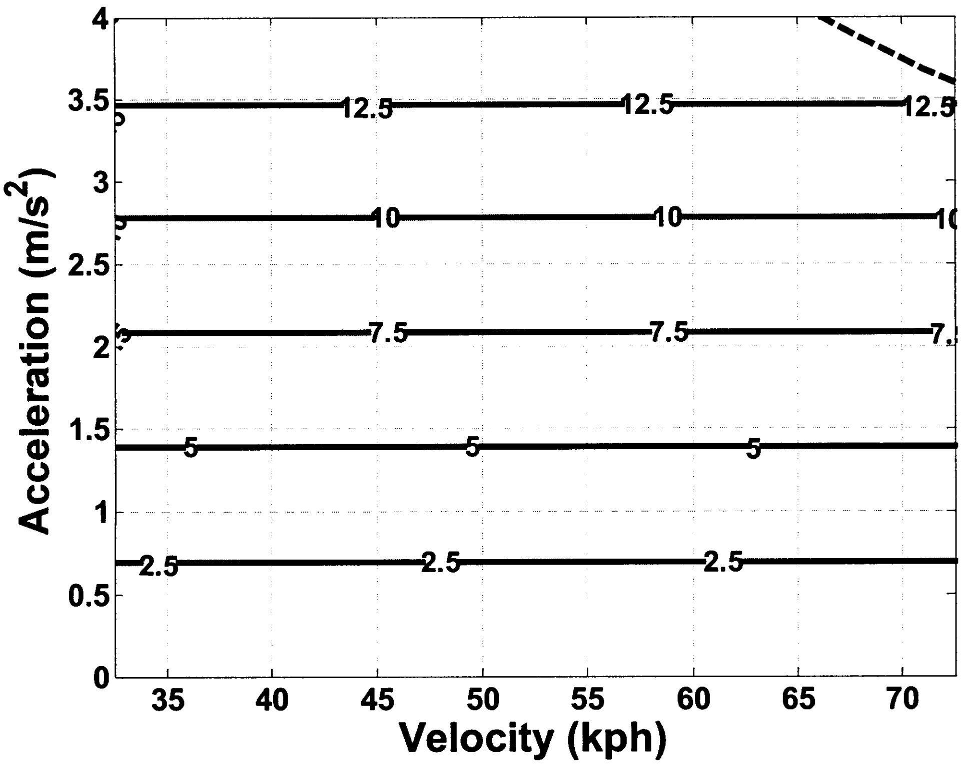

Figure 57: Instantaneous aggressiveness factor for a range of acceleration and velocities

6.2 Aggressiveness Factor for Highway Driving

Highway driving is taken as any driving with average speed greater than 45 mph (72 kph). As shown in Figure 58, for highway driving, wheel work alone is closely correlated with fuel consumption. A reference speed, in this case 45 mph, is used to shift this value to the left, as shown in Figure 59 for the 310 speed traces that fall within the highway speed band. The reference speed was chosen so that at the split the city and highway aggressiveness factors will be equal.

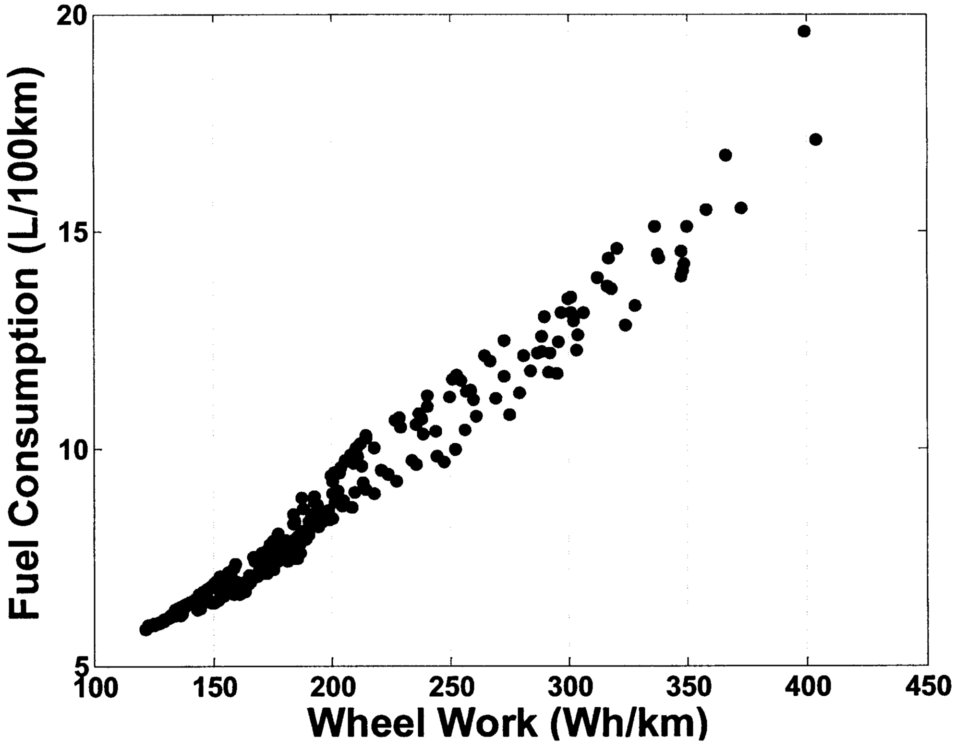

Figure 58: Fuel consumption versus wheel work for speed traces with average velocity above 45 mph (72 kph)

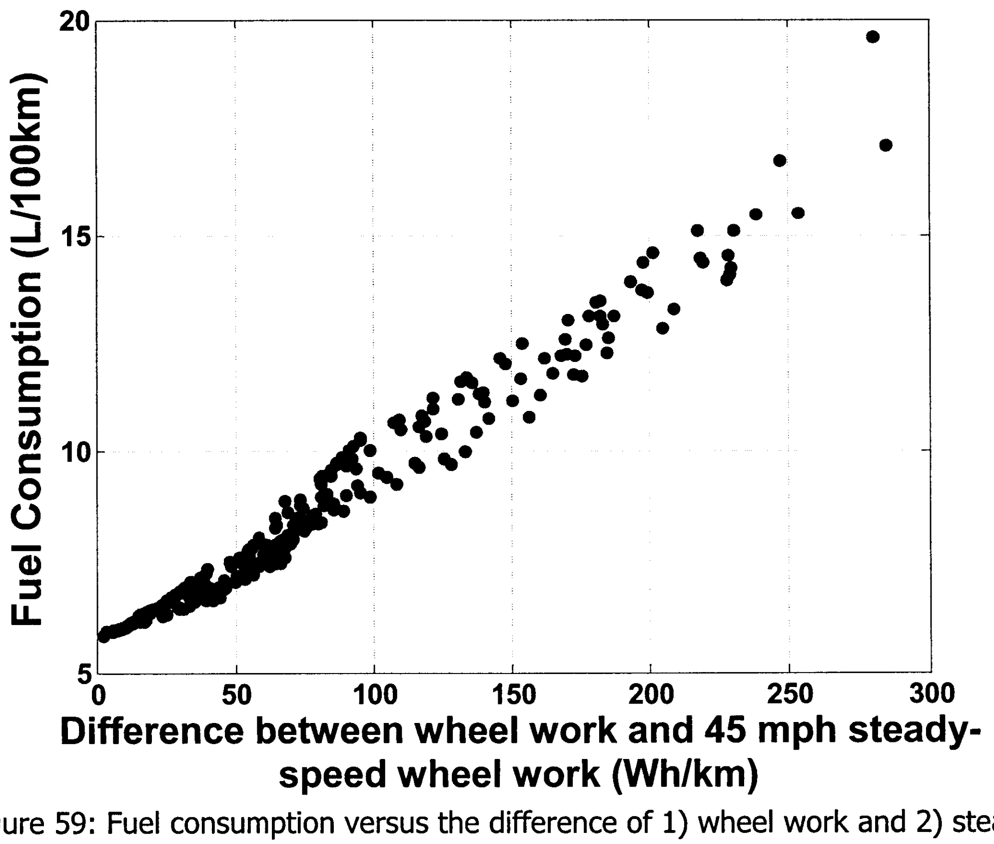

Figure 59: Fuel consumption versus the difference of 1) wheel work and 2) steady-speed wheel work at 45 mph for speed traces with average velocity above 45 mph (72 kph)

As with city driving, this wheel work value is then normalized by vehicle mass to give the aggressiveness factor (in units of acceleration). The final aggressiveness factor can be expressed in words as:

$$\text{Aggressiveness factor} = \frac{\text{Positive Wheel Work} - \text{Steady Speed Wheel Work at 45 mph}}{\text{Mass}} \tag{23}$$

And in variables:

$$A.F_{Highway} = \left(\frac{1}{M}\right)\left[\left(\frac{\int \left(Cv^3 + Bv^2 + Av + Mav\right)^+ dt}{\int vdt}\right) - \left(Roadload(20.12\ \text{m/s})\right)\right] \tag{24}$$

As shown in Figure 60, this factor is linearly related to fuel consumption. For the Ford Focus, every 1 m/s^2 increase in city aggressiveness factor causes an increase of 4.4 L/100km in fuel consumption, approximately the same as for city driving. The norm of the residuals is 7.4.

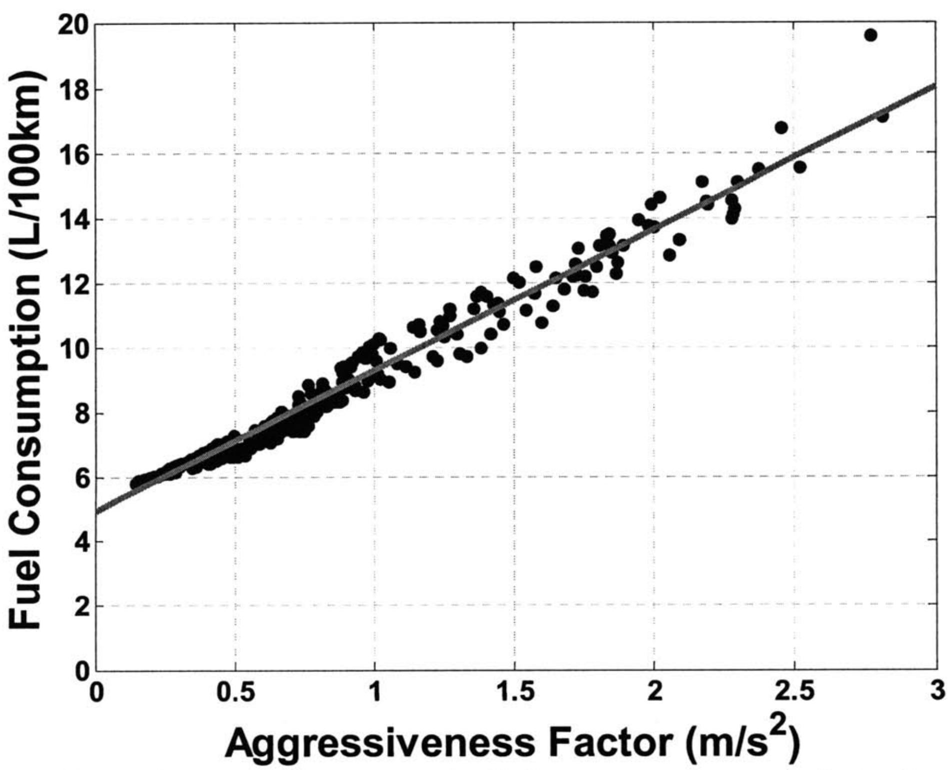

Figure 60: Fuel consumption versus the highway aggressiveness factor for speed traces with average velocity greater than 45 mph (72 kph)

Interpretation as Accelerations and Velocities

As above, the formation of the aggressiveness factor equations allows us to identify the key features of highway driving that impact fuel consumption. Here, any increase in wheel work causes a proportional increase in consumption, regardless of whether that increase in wheel work came from high acceleration or from higher average speed. As shown below, although the aggressiveness factor is still heavily dependent upon acceleration, it is also dependent on velocity. Not only does the aggressiveness factor increase at higher speeds, but so to does its sensitivity to acceleration. For illustrative purposes only, Figure 61 shows the instantaneous aggressiveness factor for the Ford Focus for a range of accelerations and highway velocities. The upper bound represents the maximum acceleration of the vehicle.

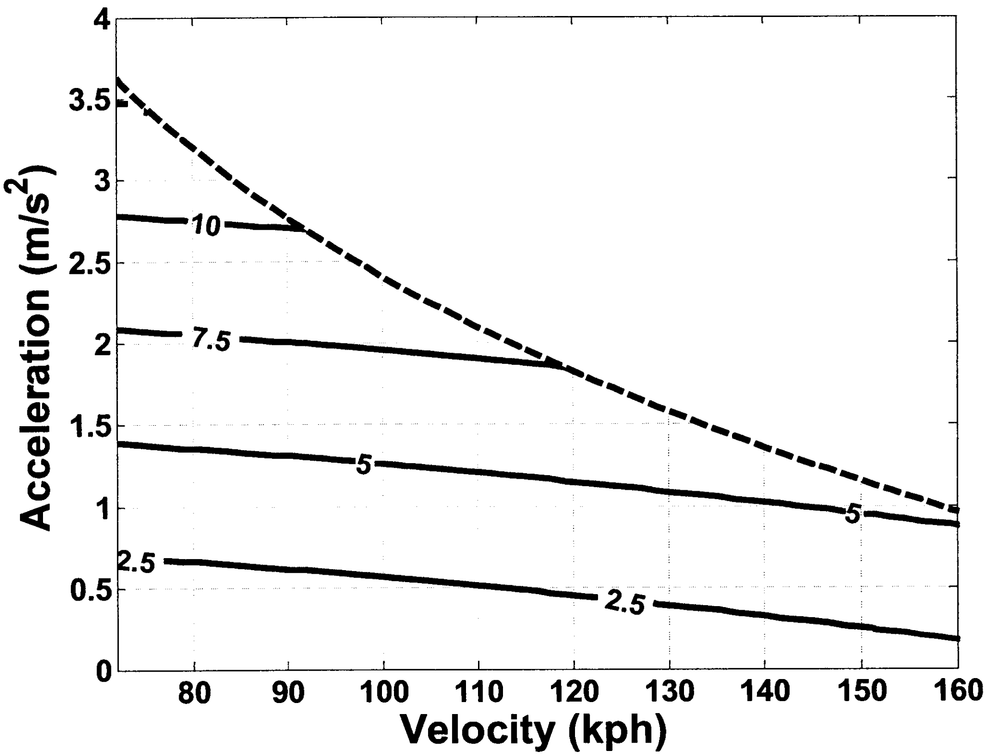

Figure 61: Instantaneous aggressiveness factors for a range of acceleration and highway velocities, bounded by maximum acceleration

6.3 Aggressiveness Factor for Neighborhood Driving

Neighborhood driving is taken as any driving with average speed less than 20 mph (32 kph) and is the most complicated to quantify. This is due primarily to the large impact of vehicle speed. As shown in Chapter 5, for steady-speed driving at less than 20 mph, vehicle efficiency falls dramatically with decreasing vehicle speed, causing dramatic increases in fuel consumption. As a result, during neighborhood driving, wheel work has very little correlation with fuel consumption, as shown in Figure 62 for the 280 speed traces that fall within the neighborhood speed band. Likewise with average positive power, as shown in Figure 63.

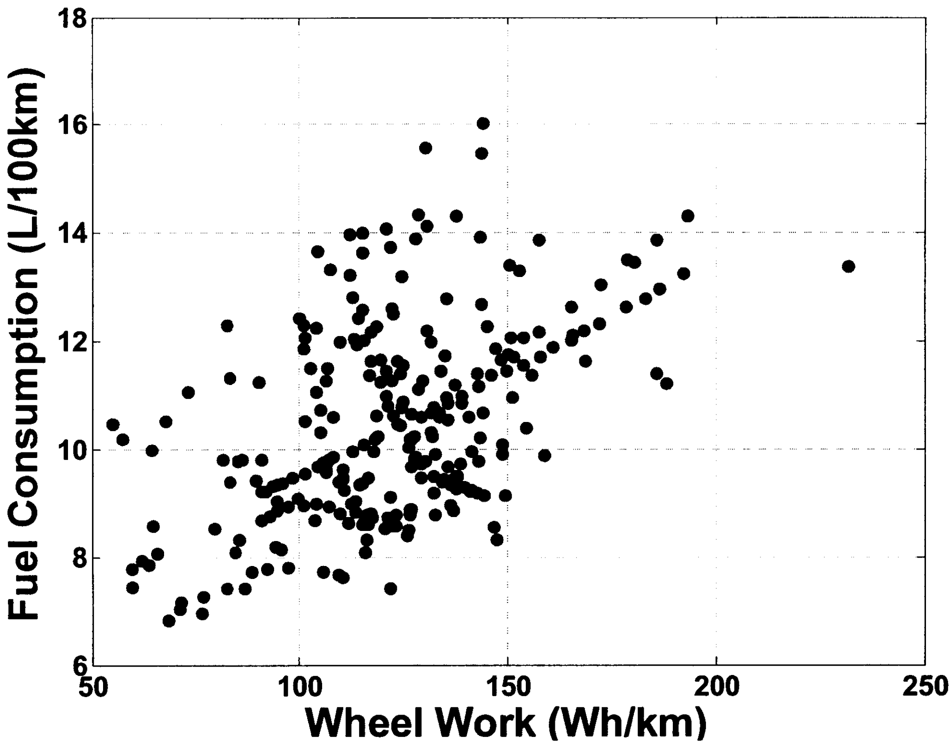

Figure 62: Fuel consumption versus wheel work for speed traces with average velocity less than 20 mph (32 kph)

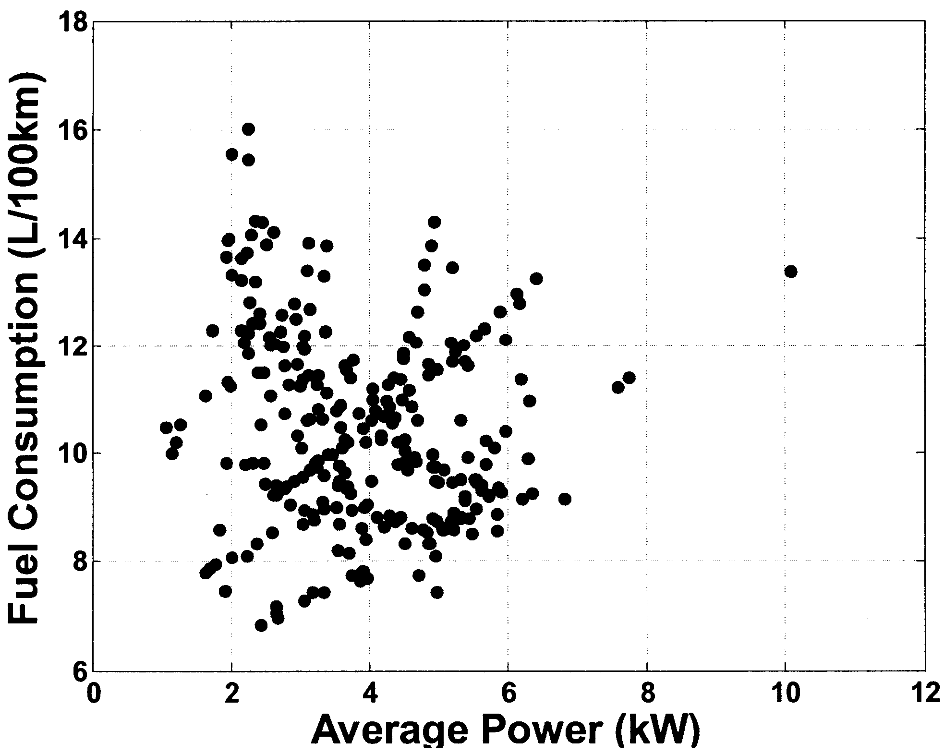

Figure 63: Fuel consumption versus average positive power for speed traces with average velocity less than 20 mph (32 kph)

In order to capture the role of average speed in fuel consumption during neighborhood driving, extra terms are needed that relate the average speed of the cycle to some reference speed. In this case, the reference speed is taken to be 20 mph (32 kph), the upper bound on neighborhood driving. First, the wheel work term (numerator) is generated by adding the acceleration wheel work of the cycle to steady-speed wheel work at 20 mph. Then, the ratio of the reference to average speed is applied as a multiplier. These terms account for the fact that vehicle efficiency decreases dramatically with decreasing vehicle speed. The reference speed was chosen to be 20 mph, in order to optimize the overall fit while maintaining a consistent trend between aggressiveness factor and fuel consumption for all neighborhood driving. A slightly higher reference speed would improve the overall fit, but selecting a reference speed above the neighborhood/city split (20 mph) distorts the trend.

This value is then normalized by vehicle mass as with city and highway driving. The final aggressiveness factor can be expressed in words as:

$$\mathrm{AF}_{\mathrm{Neighborhood}} = \left(\frac{(\text{Acceleration Wheel Work} + \text{Steady-Speed Wheel Work at 20 mph})}{\text{Mass}}\right)\left(\frac{\text{20 mph}}{\text{average speed}}\right) \tag{25}$$

And in variables:

$$\mathrm{AF}_{\mathrm{Neighborhood}} = \left(\frac{1}{M}\right)\left[\left(\frac{\int\left(Av + Bv^2 + Cv^3 + Mav\right)^{+} dt}{\int vdt}\right) - \mathrm{Roadload}(\bar{v}) + \mathrm{Roadload}(8.9\ \mathrm{m/s})\right]\left(\frac{8.9\ \mathrm{m/s}}{\bar{v}}\right) \tag{26}$$

As shown in Figure 64, this factor is linearly related to fuel consumption. For the Ford Focus, every 1 m/s^2 increase in city aggressiveness factor causes an increase of 2.6 L/100km in fuel consumption. The norm of the residuals for this fit is 7.3.

Interpretation as Accelerations and Velocities

For neighborhood driving, speed has the largest overall impact. As speed decreases, the aggressiveness factor increases, but so does the sensitivity of the aggressiveness factor to acceleration. This is shown clearly in Figure 65, which is, again, for illustrative purposes.

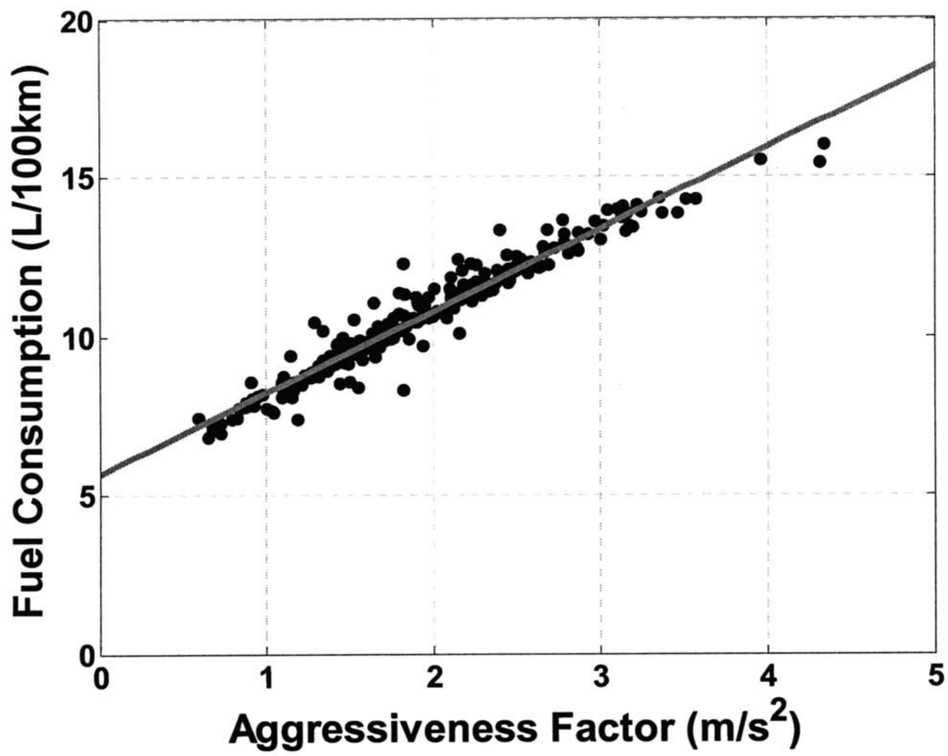

Figure 64: Fuel consumption versus the city aggressiveness factor for speed traces with average velocity less than 20 mph (32 kph)

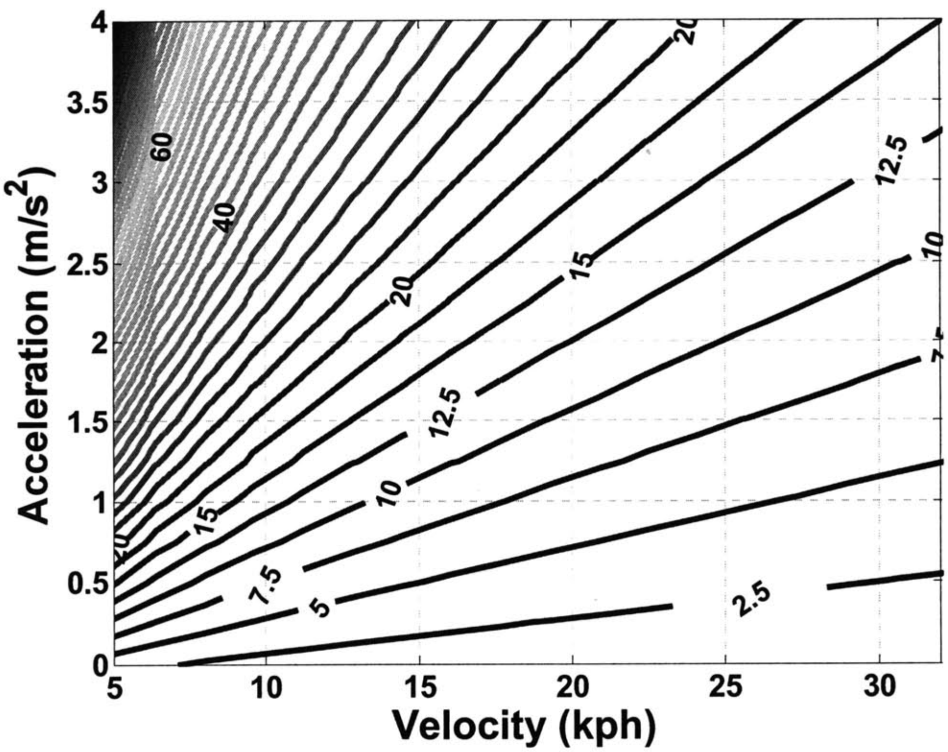

Figure 65: Instantaneous aggressiveness factors for a range of acceleration and neighborhood velocities

6.4 Using and Interpreting the Aggressiveness Factors

The aggressiveness factors are metrics that combine and quantify the impact of driving behaviors on both wheel work and vehicle efficiency. Although aggressiveness factors have the units of acceleration, they are not accelerations and are not proportional to any acceleration values. They are mass-normalized, distance-weighted measurements of the driving behaviors that increase fuel consumption. As a result, the aggressiveness factors illuminate which behaviors have the greatest impact on fuel consumption in each of the three speed bands. They also allow us to quantify driving behaviors in a way that is proportional to fuel consumption. This means that we can compare drive cycles, driving patterns, and drivers using a single metric. However, it is important to understand the key features and limitations of the aggressiveness factors.

1. *The Aggressiveness Factors are Distance-Weighted*

Aggressiveness factors weigh the impact of driving behaviors on fuel consumption by distance traveled . So as long as they are of the same type (city, neighborhood, or highway) aggressiveness factors can be combined through a linear weighting by distance. As an example, take the REP05 drive cycle. This cycle can be split into three sections, as shown in Figure 66. The first segment has average speed greater than 45 mph (72 kph) and a highway aggressiveness factor of 0.64 m/s^2. The highway aggressiveness factor for the second segment of the cycle (average speed also greater than 45 mph) is 0.48 m/s^2.

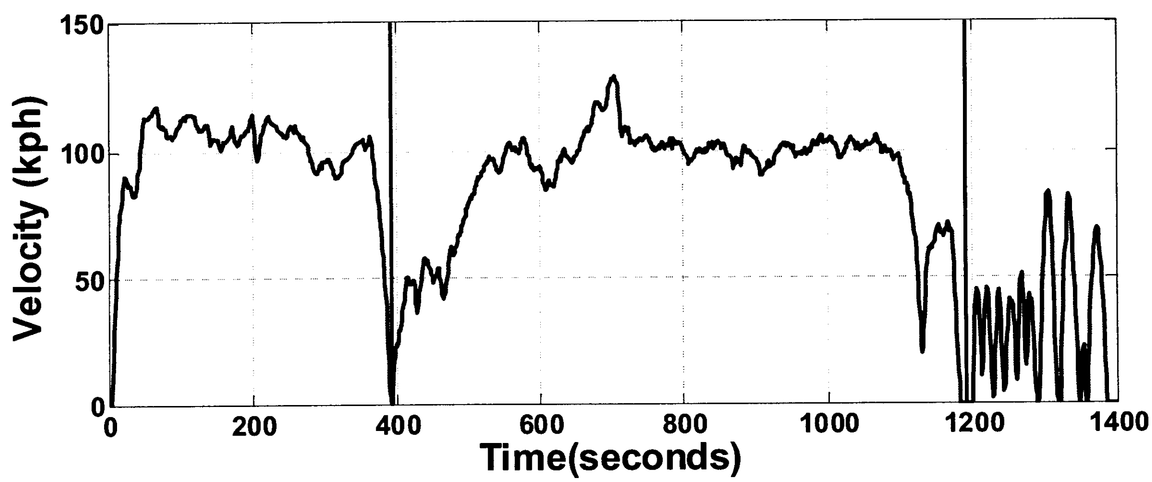

Figure 66: REP05 drive cycle split into three segments

Because the first two segments are both highway driving, the combined aggressiveness factor for this larger section of the cycle can be calculated through Equation 27:

$$AF_{1-2} = \frac{(AF_1 x_1) + (AF_2 x_2)}{(x_1 + x_2)} \tag{27}$$

Where AF_1 is the aggressiveness of the first segment and x_1 is the distance traveled during that segment. The aggressiveness for these first two segments of the REP05 is 0.54 m/s^2, which is different than if the two segment aggressiveness factors had been simply averaged.

Unfortunately, the final segment has average speed below 20 mph (32 kph) and a neighborhood aggressiveness factor of 2.94 m/s^2. In order to calculate the aggressiveness factor of the entire cycle, the wheel work and average speed of the cycle must be known. These can be calculated from the wheel work, distance, and average speed of the three segments according to:

$$W_{1-3} = \frac{(W_1 x_1) + (W_2 x_2) + (W_3 x_3)}{(x_1 + x_2 + x_3)} \qquad (28)$$

$$\bar{v}_{1-3} = \frac{(\bar{v}_1 x_1) + (\bar{v}_2 x_2) + (\bar{v}_3 x_3)}{(x_1 + x_2 + x_3)} \qquad (29)$$

Where W is the wheel work and $\bar{v}$ is the average speed of that segment. Although the aggressiveness factors are distance-weighted, average speed, which is time-weighted, has a significant effect: it determines which speed band the driving pattern falls into. And although the average speed falls into a single speed band, the driving pattern itself may contain speeds that fall into all three speed bands. As shown in Figure 67, even neighborhood driving (by average speed) can contain speeds above 45 mph. City driving patterns tend to have the greatest variability in speeds.

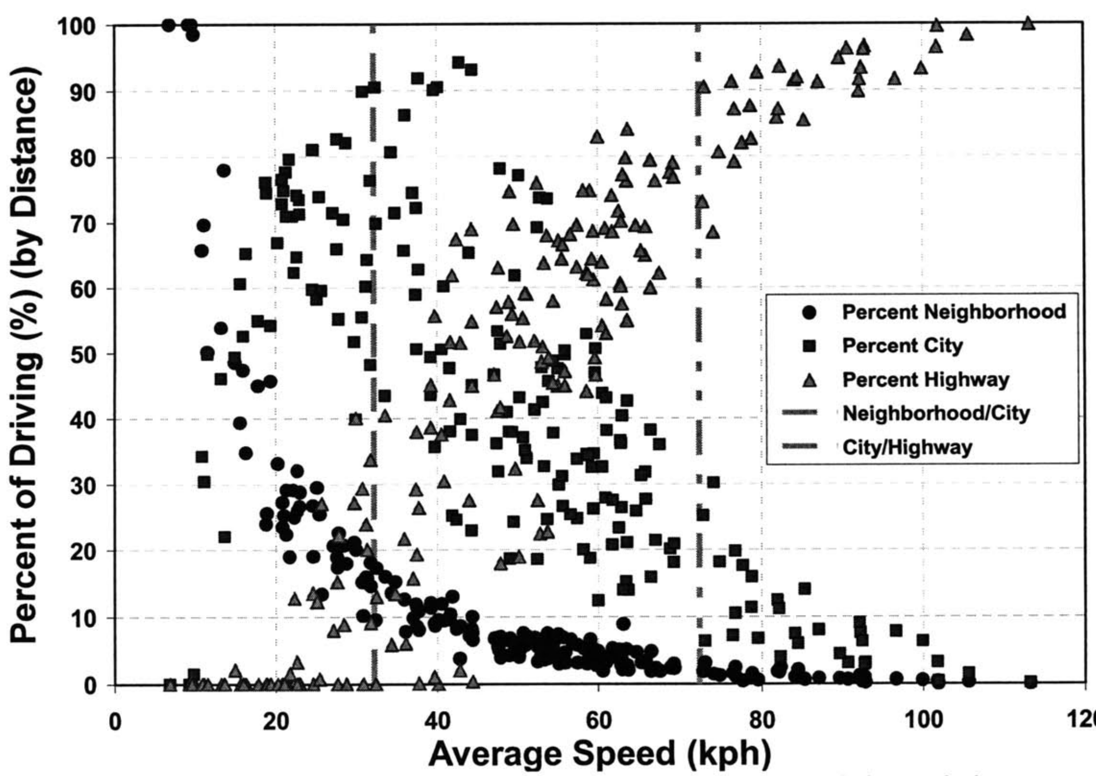

Figure 67: Distribution of speeds below 20 mph (neighborhood driving), between 20 and 45 mph (city driving), and above 45 mph (highway driving) for a mix of speed traces

Aggressiveness factors incorporate all of the driving behaviors over the entire trip, and do not reflect instantaneous behaviors. Future work could use the aggressiveness factors to derive optimal speed traces for specific trips and average speeds. For example: during neighborhood driving, does using higher accelerations in order to achieve higher speeds increase or decrease overall fuel consumption? A few seconds of very high accelerations would increase consumption during those few seconds, but achieving higher speeds sooner would decrease consumption (for neighborhood driving). The tradeoff between these two behaviors could be determined by calculating the aggressiveness factor for a variety of acceleration and speed combinations. However, this would not identify how real drivers are likely to respond, over the course of an entire trip, to using higher initial accelerations.

2. *The Three Aggressiveness Factors can not be Directly Compared*

Because they are calculated differently; even though the units are the same, the city, highway, and neighborhood aggressiveness factors can not be directly compared. This is most true for the neighborhood aggressiveness factors, as can be seen in Figure 68. Both city and neighborhood aggressiveness factors were calculated for a group of speed traces with average speed below 45 mph (72 kph). The squares represent city speed traces. The triangles represent neighborhood speed traces. And the circles represent the speed traces, some city, some neighborhood, which are within 5 kph of the 32 kph (20 mph) split. City aggressiveness factors underestimate the aggressiveness of low speed cycles; and neighborhood aggressiveness factors tend to overestimate the aggressiveness of the city cycles. In both cases, the difference between the two aggressiveness factors increases for speed traces farthest from the split.

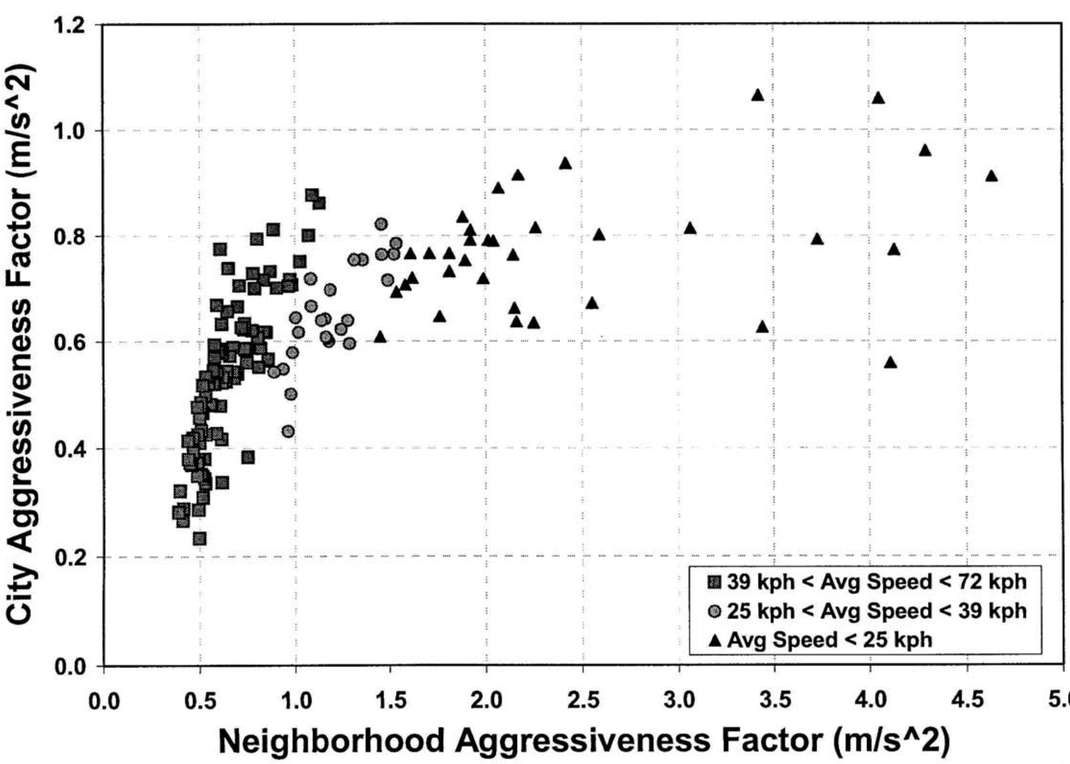

Figure 68: City versus neighborhood aggressiveness factors for the same speed traces for a set of speed traces with average speeds less than 45 mph

The relationship between the highway and city aggressiveness factors, while still dominated by speed, has a different effect. In Figure 69, the squares represent city speed traces. The triangles represent highway speed traces. And the circles represent the speed traces, some city, some highway, which are within 5 kph of the 72 kph (45 mph) split. In addition, three sets of speed traces with the same average speed were selected and fit with linear trend lines. As can be seen, as the difference between average speed and the split increases, the slope between the two aggressiveness factors remains the same (roughly 1), while the intercept changes. This is important. It means that while city and highway aggressiveness factors can not be directly compared, changes in city and highway aggressiveness factors can be compared, and that a decrease in a city aggressiveness factor will cause the same reduction in fuel consumption as a similar decrease in a highway aggressiveness factor.

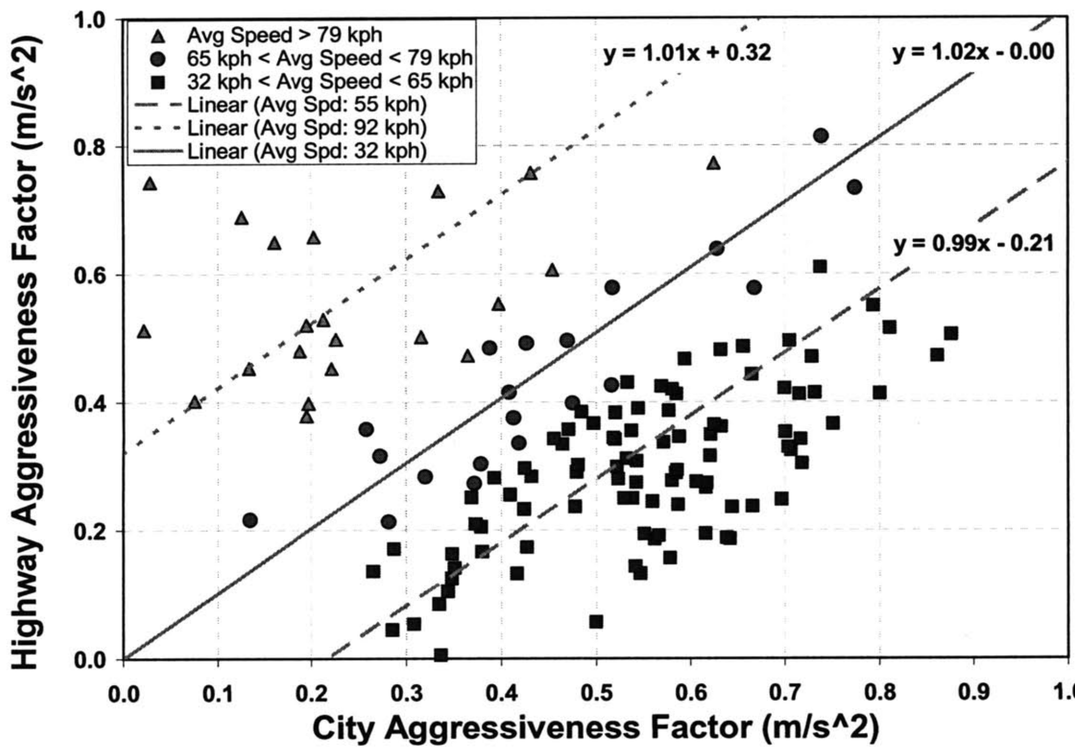

Figure 69: Highway versus city aggressiveness factors for the same speed traces for a set of speed traces with average speeds above 20 mph

3. Aggressiveness Factors Vary Slightly Between Vehicles

Although the aggressiveness factors are normalized by vehicle mass, they are vehicle-specific in that they involve the wheel work of a specific vehicle driven over a specific drive cycle. As a result, the aggressiveness of a single drive cycle will differ slightly for any two vehicles. This variation is dominated by 1) difference in the actual driven speed and 2) differences in the coastdown aerodynamic drag and rolling resistances. However, as will be shown, the differences in aggressiveness factors are small, meaning that, in a general sense, aggressiveness factors from one vehicle can be projected to others.

As discussed earlier, both human drivers and the PSAT driver model influence the speed trace that the vehicle actually follows, causing it to differ from the original speed schedule. Because of the driver effects, the speed trace driven by the Explorer is slightly different from that driven by the Focus and slightly different from that driven by the Civic. These differences affect wheel work, average speed, and, consequentially, the aggressiveness factor. However, as demonstrated in Figure 70 for the Ford Focus, the resulting differences in the aggressiveness factors are very slight, at least for PSAT-simulated driving.

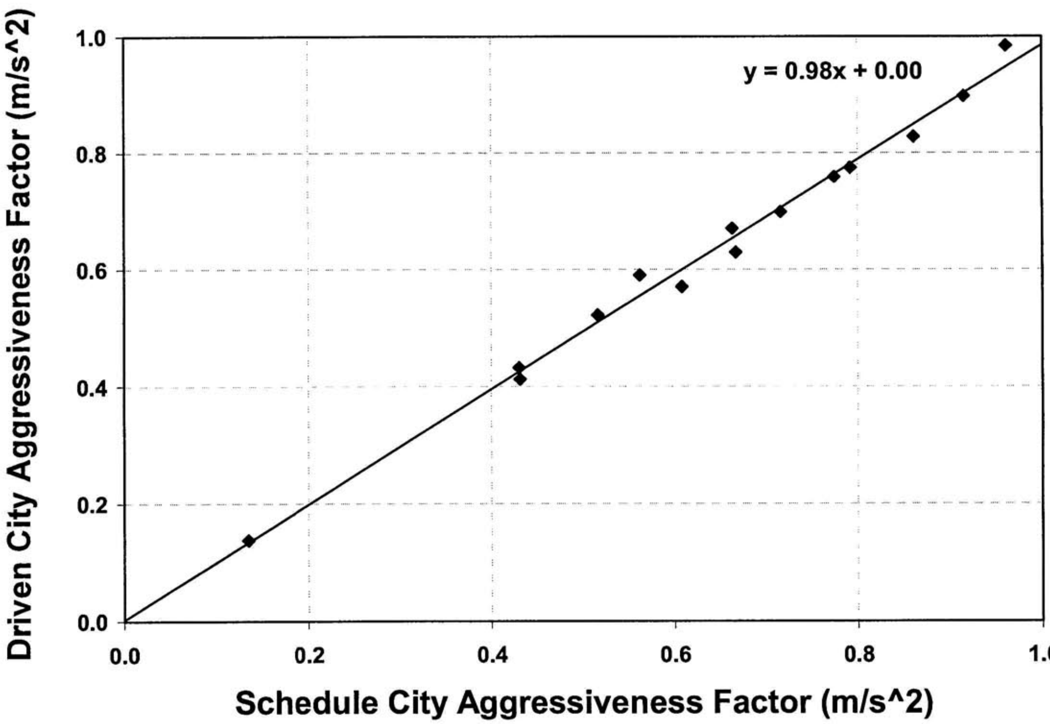

Figure 70: Driven versus schedule aggressiveness factors for a set of city speed traces simulated using PSAT and the Ford Focus vehicle model

Differences in vehicle coastdown coefficients account for the majority of the differences in aggressiveness factors between vehicles. However, the magnitude of the impact depends largely on the specifics of the drive cycle. For example as shown in Table 21 and Table 22, both the Civic and the Explorer tend to have slightly higher aggressiveness factors than the Focus for city and highway driving. For neighborhood speed traces, Table 23, the Civic has lower aggressiveness factors, while the Explorer has equivalent or slightly lower aggressiveness factors.

Table 21: Schedule Aggressiveness Factors (m/s^2) for City Speed Traces

	Focus	Civic	Explorer
UDDS	0.57	0.60	0.61
SC03	0.67	0.71	0.73
ARB02	0.77	0.82	0.84
LA92	0.86	0.91	0.92

Table 22: Schedule Aggressiveness Factors (m/s^2) for Highway Speed Traces

	Focus	Civic	Explorer
HWFET	0.22	0.23	0.23
REP05	0.61	0.65	0.65
US06	0.81	0.85	0.88

Table 23: Schedule Aggressiveness Factors (m/s^2) for Neighborhood Speed Traces

	Focus	Civic	Explorer
NY City	3.08	2.88	3.07
INRETS URB	1.49	1.39	1.48
INRETS URB3	1.81	1.66	1.77

4. *Sensitivity of Fuel Consumption to Aggressiveness Varies between Vehicles*

Some vehicles are more sensitive to changes in aggressiveness than others. This is true even though the aggressiveness factors use the vehicle coastdown coefficients and mass. As shown in Figure 71 for a set of city speed traces, the relationships between aggressiveness factor and fuel consumption for the Focus, Civic, and Explorer are linear, but with different slopes and intercepts. Normalizing by the fuel consumption of a specific drive cycle tends to magnify the differences. However, as shown in Figure 72, normalizing fuel consumption by vehicle weight collapses the three curves to a much tighter fit. Once fuel consumption is weight-normalized; engine power, aerodynamics, and transmission design likely help explain the differences in the slope between fuel consumption and aggressiveness. For the three vehicles shown, the lower the engine power, the more sensitive mass-normalized fuel consumption is to increases in aggressiveness. The same trend applies for both neighborhood and highway aggressiveness factors, although for highway driving, Figure 73, aerodynamics seems to play a larger role. Additional work would be needed to quantify the effect of specific vehicle behaviors.

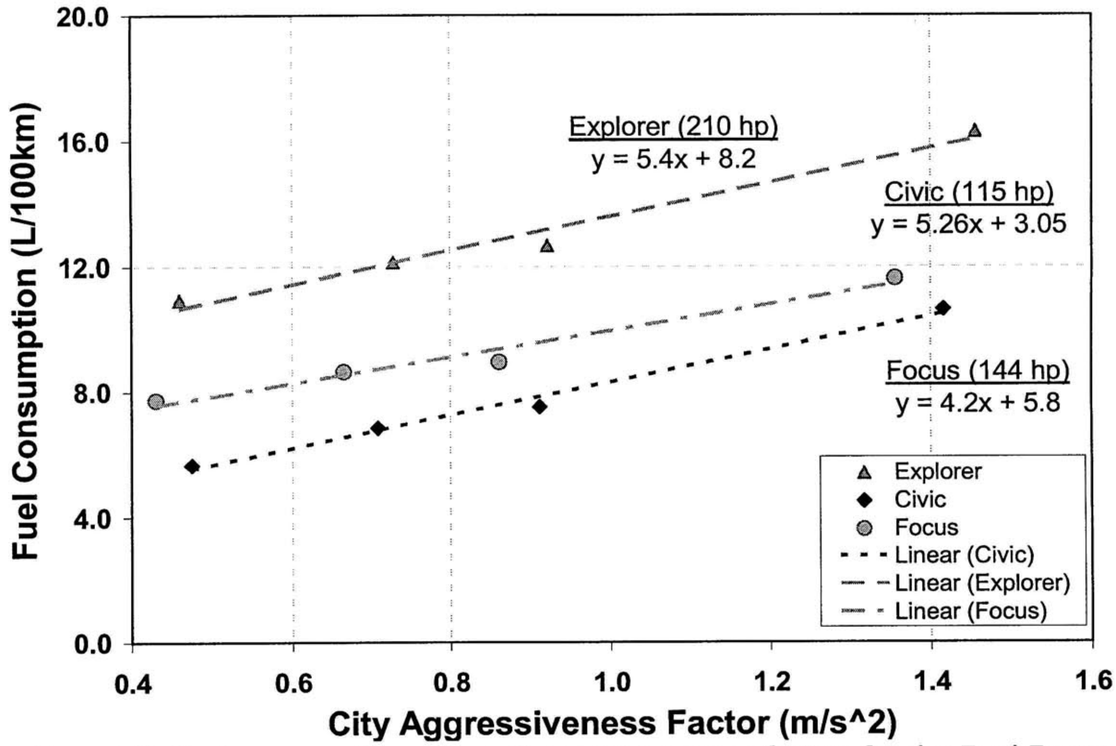

Figure 71: Fuel consumption versus city aggressiveness factors for the Ford Focus, Honda Civic, and Ford Explorer

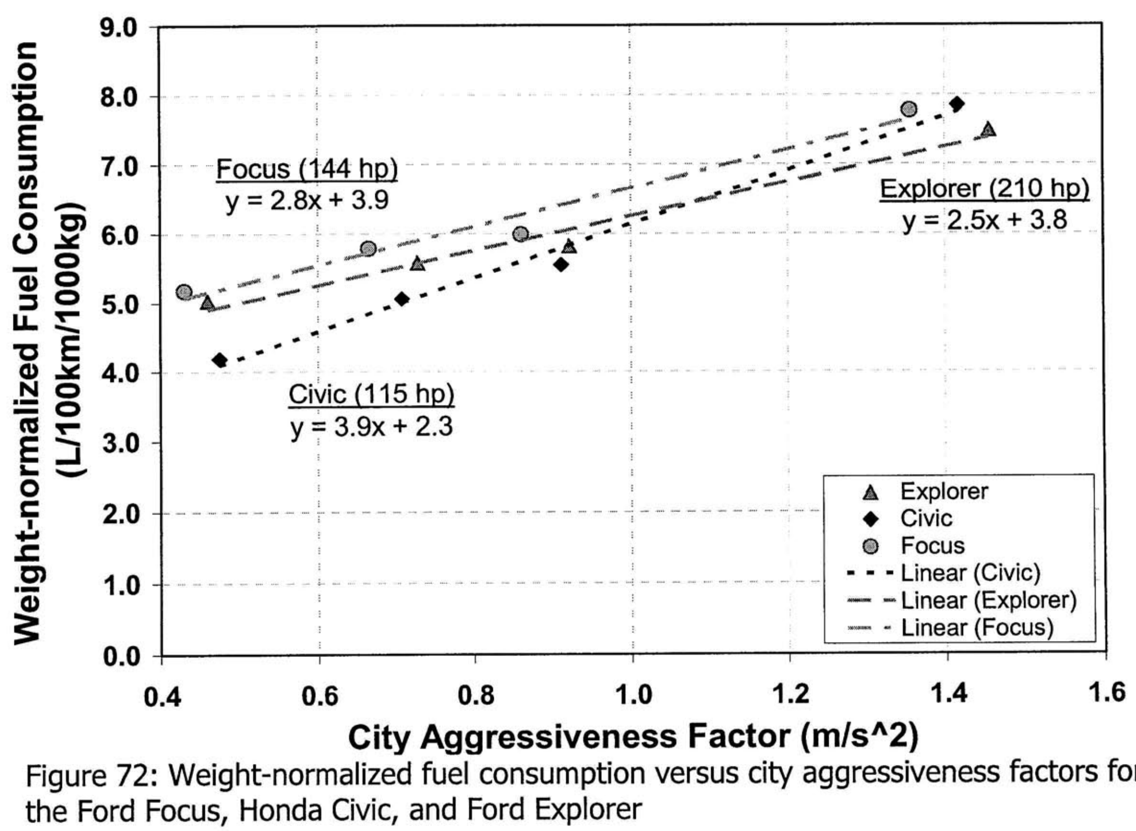

Figure 72: Weight-normalized fuel consumption versus city aggressiveness factors for the Ford Focus, Honda Civic, and Ford Explorer

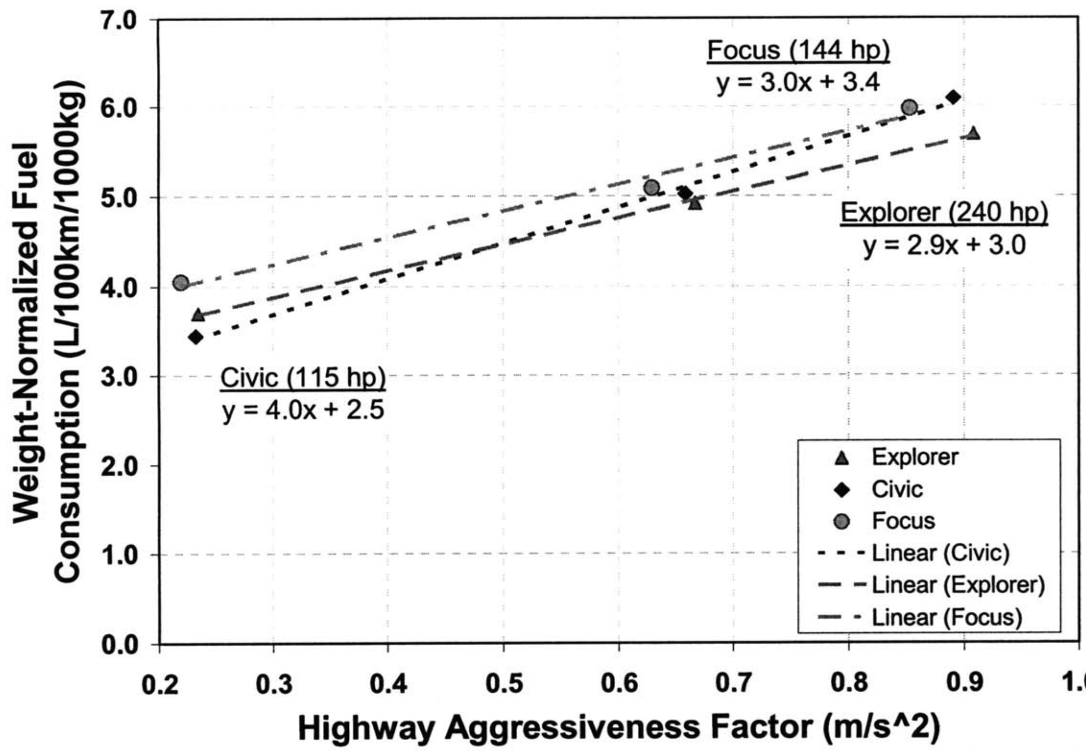

Figure 73: Weight-normalized fuel consumption versus highway aggressiveness factors for the Ford Focus, Honda Civic, and Ford Explorer

6.5 Aggressiveness of Standard Drive Cycles

One use of the aggressiveness factors is to compare standard drive cycles to each other and to real-world driving. Table 24 lists the fuel consumption and aggressiveness factor for the Ford Focus for a range of drive cycles from the U.S., Europe, and Japan. These cycles are shown graphically in Appendix A. The four cycles used for the new EPA labels are highlighted. Of the neighborhood cycles, the FTP falls between the ECE and Japan 10-mode cycle. Only one of the four U.S. regulatory drive cycles is a city cycle: the SC03. This cycle has similar aggressiveness as the NEDC and is much more aggressive than the EUDC and Japan15 cycles. The newer U.S. cycles, the ARB02 and LA92 are the most aggressive city cycles. Of highway drive cycles, the HWFET and the US06, both regulatory U.S. cycles are the least and most aggressive, respectfully. Neither the E.U. nor Japan has a regulatory drive cycle with average speed greater than 72 kph.

Table 24: Fuel consumption and aggressiveness factor for the Ford Focus for standard drive cycles organized by type of driving. The four drive cycles included in the new (2008+) U.S. EPA fuel economy labels are highlighted.

Drive Cycle	Fuel Consumption (L/100km)	Cycle Description	Aggressiveness Factor (m/s^2)
Neighborhood Cycles			
Japan10/15	9.36	Japanese Reg.	1.53
FTP	8.39	U.S. Reg.	1.54
Japan10	10.67	Japanese Reg.	1.76
ECE	10.52	European Reg.	1.77
INRETS urb	10.67	Other European	1.92
INRETS urb3	11.36	Other European	2.15
INRETS urb1	11.38	Other European	2.17
NY City	16.02	Other U.S.	4.29
City Cycles			
EUDC	6.76	European Reg.	0.41
Japan15	7.74	Japanese Reg.	0.44
INRETS road2	7.21	Other European	0.52
INRETS road1	7.83	Other European	0.56
NEDC	8.14	European Reg.	0.63
SC03	8.64	U.S. Reg.	0.67
INRETS road	7.91	Other European	0.72
ARB02	8.75	Other U.S.	0.77
LA92	8.95	Other U.S.	0.86
Highway Cycles			
HWFET	6.05	U.S. Reg.	0.22
Rep05	7.61	Other U.S.	0.61
INRETS hwy	8.03	Other European	0.76
INRETS hwy1	8.61	Other European	0.77
US06	8.92	U.S. Reg.	0.81

6.6 Summary of Aggressiveness Factors

In this chapter, equations for quantifying the driving behaviors based on how they impact fuel consumption have been proposed, as summarized in Table 25. These aggressiveness factors are mass-normalized and distance-weighted. Within each speed band, the aggressiveness factor is proportional to fuel consumption. Table 26 list the linear fits between the three aggressiveness factors and the fuel consumption of the Ford Focus vehicle model. These equations will be used in Chapter 7 to estimate the fuel savings due to specific driving behaviors. Although the aggressiveness factors vary slightly between vehicles, general trends remain the same. Because of these characteristics, the aggressiveness factors are ideal for evaluating driving data to provide insight into the aggressiveness of real-world driving.

Table 25: Summary of aggressiveness factors, speed bands, and equations

Aggress. Factor	Speed Band (mph)	Equation
Neigh.	< 20	$\left(\frac{1}{M}\right)\left[\left(\frac{\int\left(Av+Bv^2+Cv^3+Mav\right)^+dt}{\int vdt}\right)-\mathrm{Roadload}(\bar{v})+\mathrm{Roadload}(8.9\ \mathrm{m/s})\right]\left(\frac{8.9\ \mathrm{m/s}}{\bar{v}}\right)$
City	20 - 45	$\left(\frac{1}{M}\right)\left[\left(\frac{\int\left(Av+Bv^2+Cv^3+Mav\right)^+dt}{\int vdt}\right)-\left(Roadlaod(\bar{v})\right)\right]$
High.	> 45	$\left(\frac{1}{M}\right)\left[\left(\frac{\int\left(Cv^3+Bv^2+Av+Mav\right)^+dt}{\int vdt}\right)-\left(Roadload(20.12\ \mathrm{m/s})\right)\right]$

Table 26: Linear fits between aggressiveness factors and fuel consumption of the Ford Focus

Aggressiveness Factor	Equation for Ford Focus fuel consumption
Neighborhood	$FC_{Focus}=2.56*AF_{Neighborhood}+5.65$
City	$FC_{Focus}=4.39*AF_{City}+5.14$
Highway	$FC_{Focus}=4.36*AF_{Highway}+4.95$

7 Real-World Driving

Having developed a metric to quantify driving aggressiveness in the previous chapter, this chapter moves on to an assessment of real-world driving. As discussed in Chapter 3, two sets of driving data are used: part of the 100-Car Study data and a limited set of driving patterns logged using CarChips. Based on the linear relationship between aggressiveness and fuel consumption, although no corresponding fuel consumption data is available, the fuel savings of reducing aggressiveness are estimated.

7.1 Driving in the 100-Car Study

The 100-Car Study data is used to provide illustrative driving aggressiveness values and to assess the role of vehicle performance (power-to-weight ratio) in aggressiveness. The data is evaluated based on speed and acceleration frequency distributions (SAFDs), not by trip. These results are not intended to represent "average" driving. First, the accumulated data from all eleven vehicle groups are assessed. Then the data is examined by group, and finally, potential fuel savings are estimated.

Accumulated Results

The average speed of the entire data set is 50 kph, falling within the city speed range. This means that a city aggressiveness factor applies and that acceleration wheel work dominates fuel consumption. When the driving data is separated by time in each speed band, roughly a third of the time is at city speeds (between 20 and 45 mph), roughly a third is at highway speeds (above 45 mph), and roughly a third of the time is at neighborhood speeds (less that 20 mph). Figure 74 shows the distribution of driving time for the 20 speed bins of the 100-Car Study (there were no samples in the top two bins), separating driving with accelerations and decelerations less than 1 m/s^2 (or -1 m/s^2 for decelerations) from those at higher accelerations and decelerations. Only 3 percent of driving time is at speeds above 113 kph (70 mph).

By distance, a much larger percent of driving is at high speeds, as shown in Figure 75. Close to 60 percent of the distance is traveled at highway speeds, and over 7 percent is traveled at speeds greater than 113 kph (70 mph). As a result, much of the acceleration wheel work that contributes to the city aggressiveness factor (since average speed is between 20 and 45 mph) comes from these highway speeds.

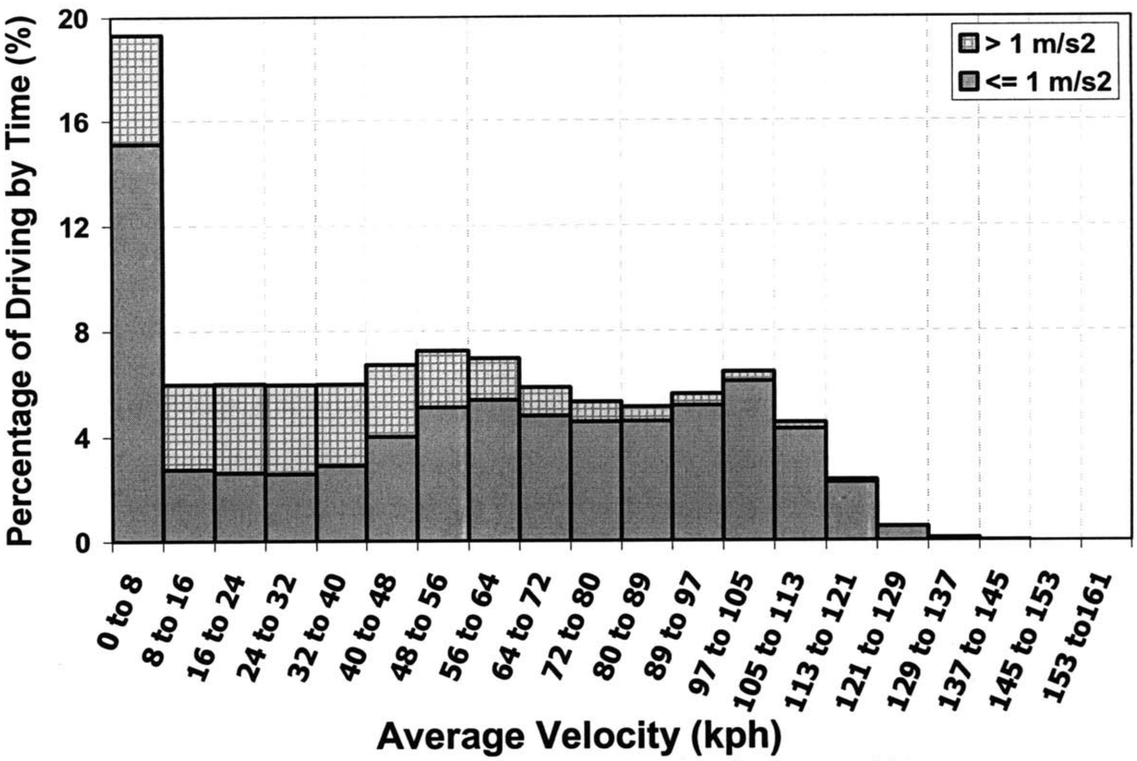

Figure 74: Percentage of driving, by time, in each vehicle speed bin

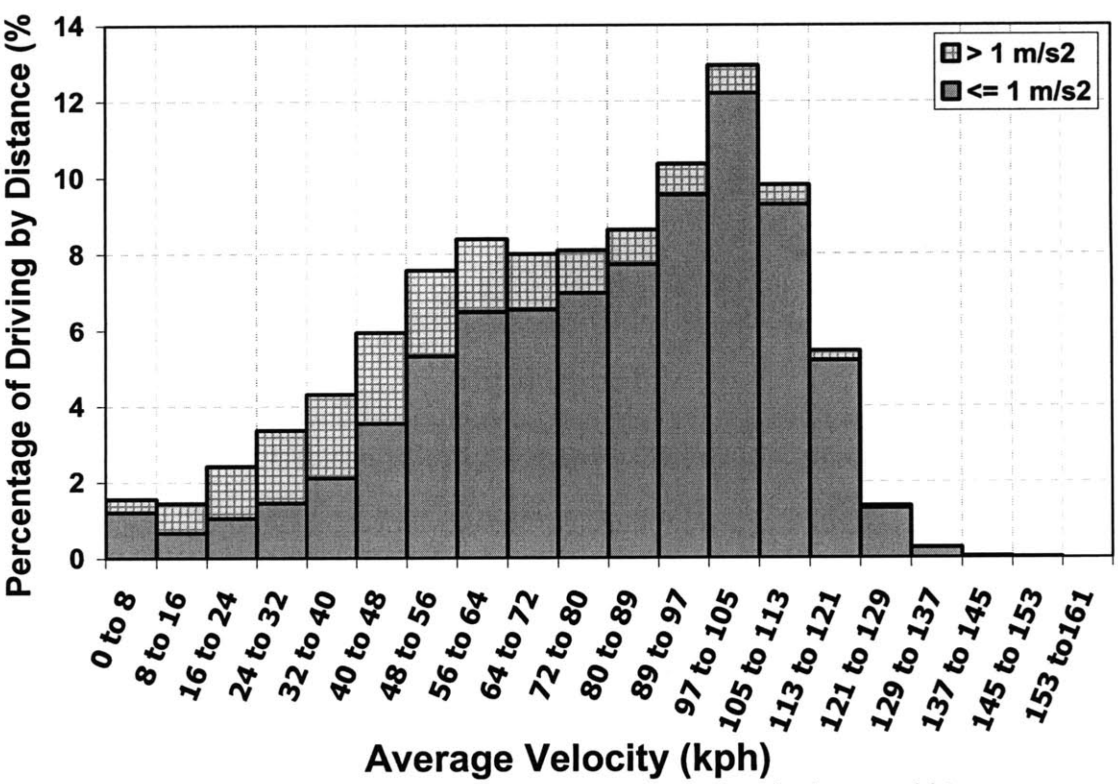

Figure 75: Percentage of driving, by distance, in each vehicle speed bin

Only a small percentage of driving is at high accelerations. Figure 76 shows, for each speed bin, both 1) the maximum acceleration bin and 2) the percent of total distance traveled with accelerations less than 1 m/s^2. Accelerations are the highest percentage of driving between 8 and 48 kph (5 to 30 mph). For highway driving, almost 100 percent of driving is at accelerations less than 1 m/s^2. In total, over 70 percent of all driving has accelerations and decelerations less then 1 m/s^2, and only 1 percent of driving has accelerations and decelerations above 3 m/s^2. However, accelerations greater than 7 m/s^2 are observed in the data set. This is much higher than the highest accelerations present in even the 90s drive cycles (the US06, LA92, ARB02, and REP05). Gonder et al. [2007] found similar aggressiveness in driving data collected in and around Kansas City. The maximum accelerations are much higher for low speed driving than for high speed driving.

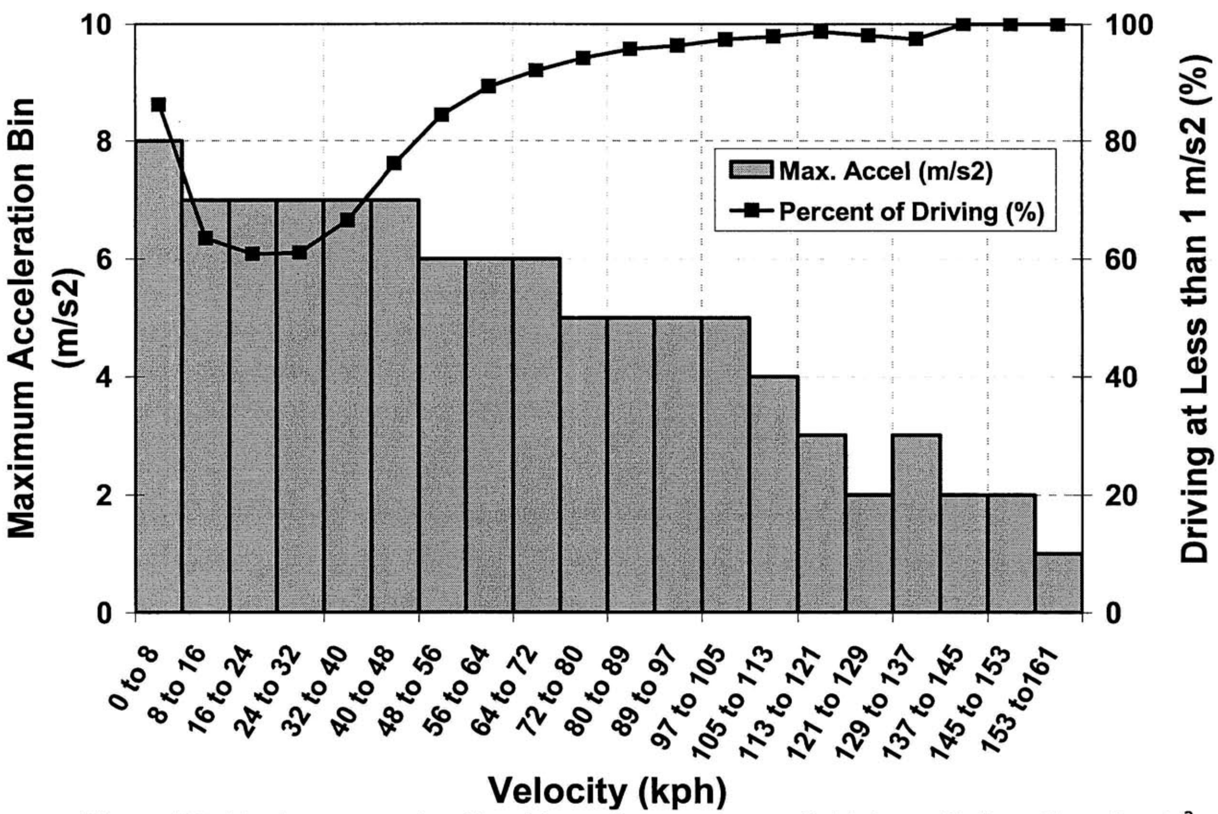

Figure 76: Maximum acceleration bin and percentage of driving with less than 1 m/s^2 acceleration versus speed bin. Percentages are by distance of travel.

Aggressiveness factors were calculated for each of the eleven vehicle groups, using the group SAFD and the coastdown coefficients and mass of the specific vehicle make and model, provided in Table 29 in Appendix B. For each group, based on the average speed of the data, a city aggressiveness factor was calculated, despite that all of the data, including very low and very high speeds was included for each group. For the aggressiveness factor for the accumulated data, the coefficients and mass of the Ford Focus were used. The aggressiveness of the accumulated data (also a city aggressiveness factor) is 0.80 m/s^2, falling between the ARB02 and LA92 drive cycles. A Ford Focus driven with this level of aggressiveness would have a fuel consumption of 8.65 L/100km (a fuel economy of 27.2 mpg). Treating each group as a single data point, the distribution of aggressiveness factors, Figure 77, follows a roughly lognormal fit.

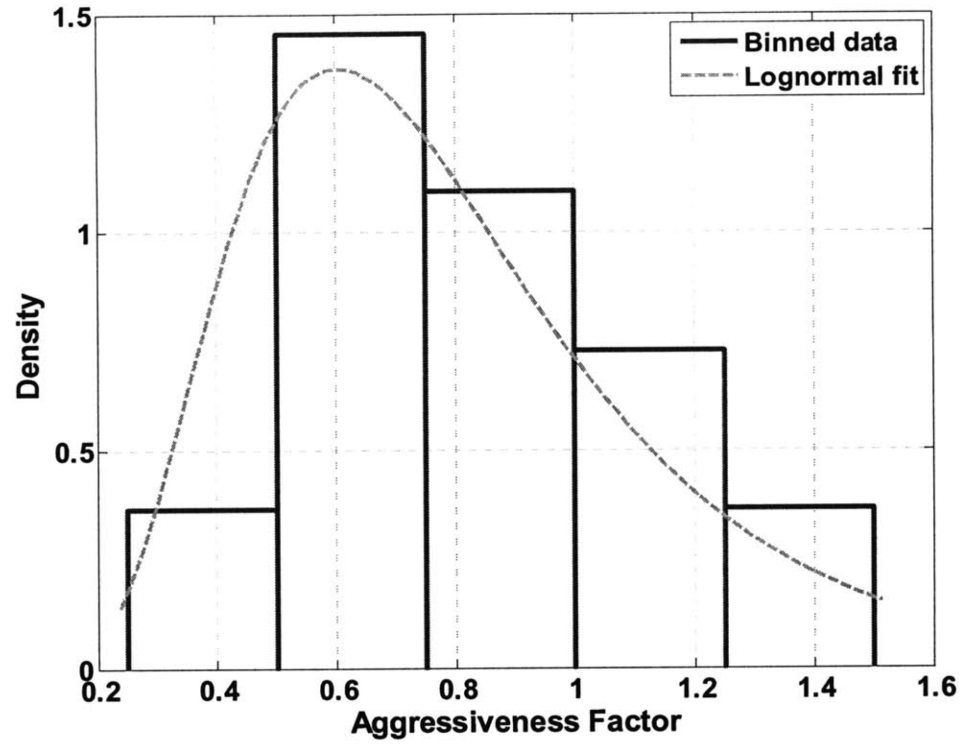

Figure 77: Probability distribution of city aggressiveness factors by vehicle group

By Make, Model, and Power-to-Weight Ratio

One of the main benefits of the 100-Car Study is that the results can be separated by vehicle make, model, and power-to-weight ratio to provide insight into how and if driving style is related to vehicle type. When the vehicle groups are separated, as shown in Figure 78 by power-to-weight ratio, average speed of each group is between 40 and 60 kph (64 and 97 mph).

There is no trend between the percentage of driving in each speed band and vehicle power-to-weight ratios. By distance, the lowest percentage of driving for each group is in the neighborhood speed band, as shown in Figure 79. The percentage of distance at these low speeds is relatively consistent across all eleven vehicle groups, varying between 6 and 11 percent. The highest percentage of distance is traveled at highway speeds. Groups 2 (Ford Taurus with 0.038 hp/lb) and 11 (Ford Taurus with 0.062 hp/lb) have substantially more highway driving, and corresponding less city driving than the other nine groups.

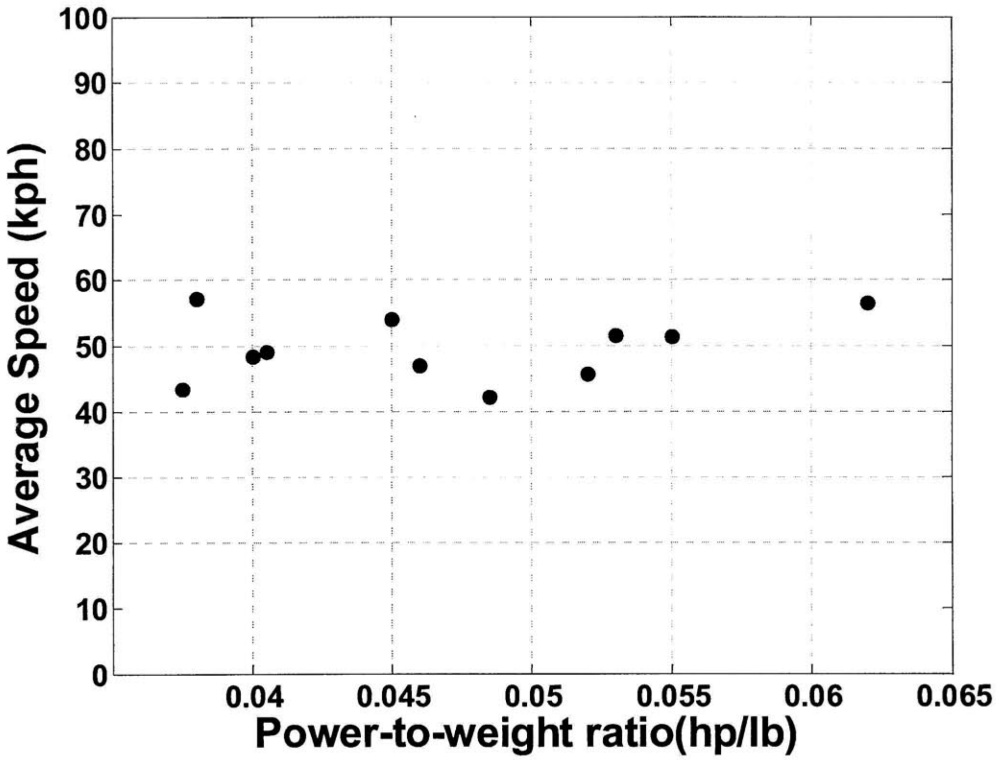

Figure 78: Average speed versus power-to-weigh ratio by group

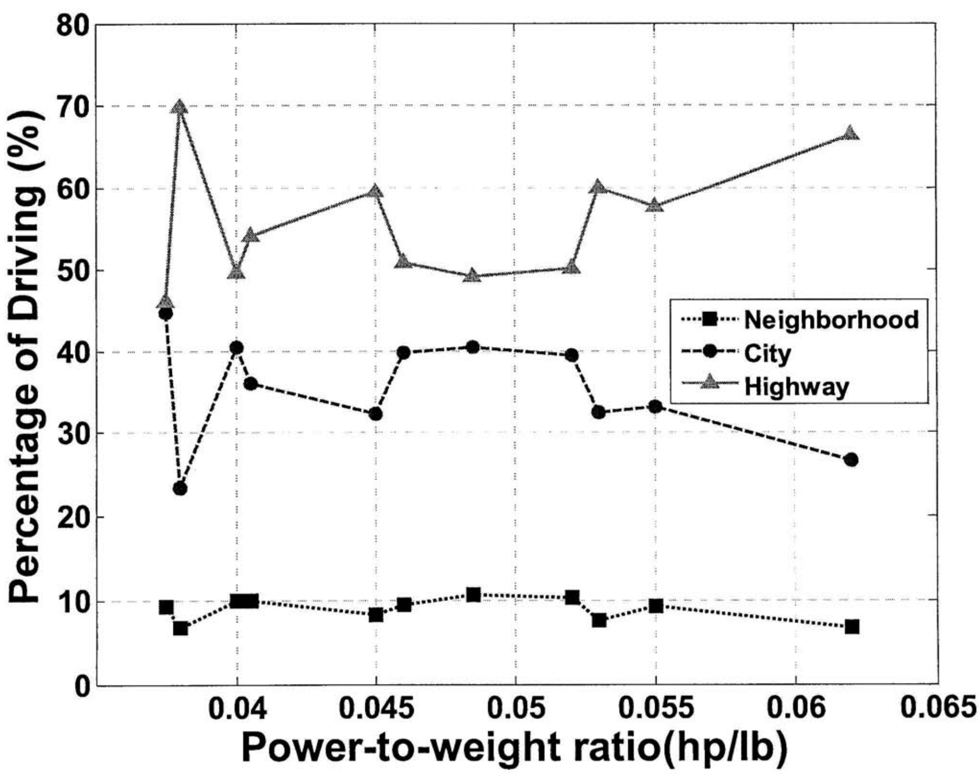

Figure 79: Percentage of driving by distance versus power-to-weigh ratio

Due to the average speed of each group (Figure 78), city aggressiveness factors are calculated. As shown in Figure 80, the aggressiveness factors of the groups vary considerably, with a range of roughly 1 m/s^2 between the minimum and maximum values. For the Ford Focus, a decrease in city aggressiveness of this magnitude would reduce fuel consumption by 4.4 L/100 km.

Of the eleven groups, aggressiveness peaks at 1.3 m/s^2 for group 5 (Chevy Malibu with 0.045 hp/lb) and reaches a minimum at 0.3 m/s^2 for group 1 (Ford Explorer with 0.0375 hp/lb). Below 0.045 hp/lbs, aggressiveness falls considerably. Above 0.045 hp/lbs, aggressiveness falls, but more gradually, with groups 9 (Toyota Camry with 0.055 hp/lb) and 10 (Ford Taurus with 0.062 hp/lb) having relatively similar aggressiveness factors. Six of the eleven groups are more aggressive than the U.S. drive cycles developed in the 90s, (the SC03, ARB02, and LA92). Only three of the vehicle groups are less aggressive than all three of these cycles.

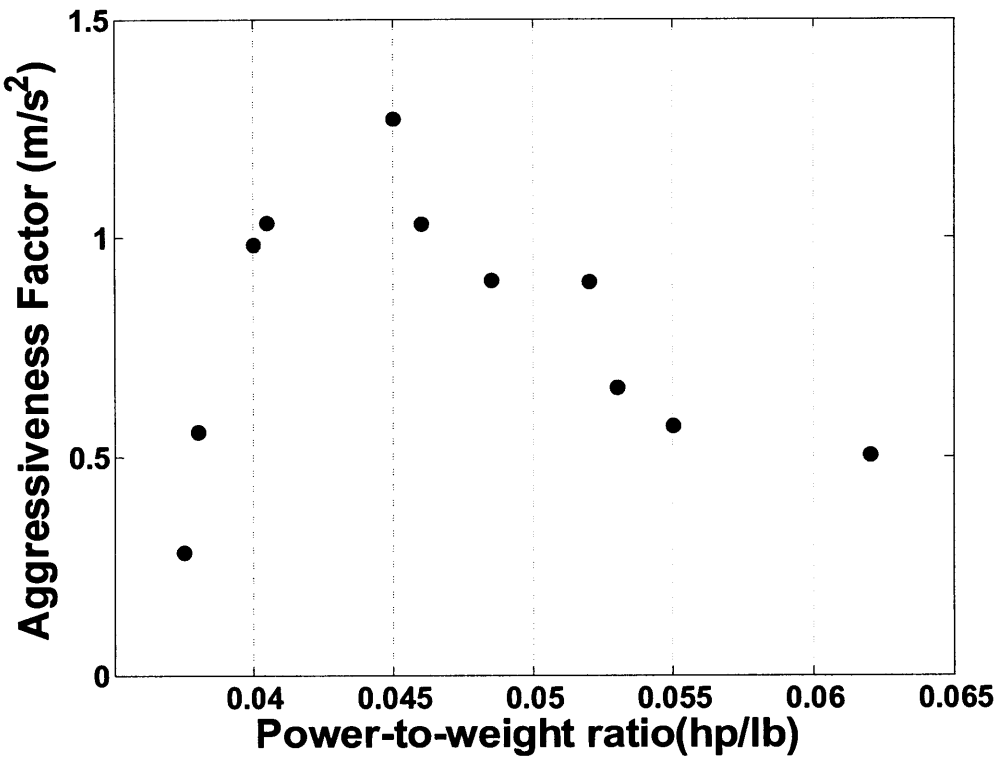

Figure 80: Aggressiveness factors versus power-to-weigh ratio by group

The trend of peaking aggressiveness at moderate vehicle performance is consistent across vehicle makes and models. Figure 81 shows aggressiveness factor versus power-to-weight ratio for the four makes and models that occur at multiple power-to-weight ratios. For the Chevy Malibu and Toyota Camry, aggressiveness decreases with increasing power-to-weight ratio. For the Ford Explorer, aggressiveness increases, and for the Ford Taurus, aggressiveness is roughly constant across the three power-to-weighs. However, all fit the trend of peaking aggressiveness for moderate performance vehicles. None of 1) torque-to-weight, 2) number of vehicles, 3) distance traveled, or 4) leased versus privately owned vehicles explain the variation in aggressiveness between groups.

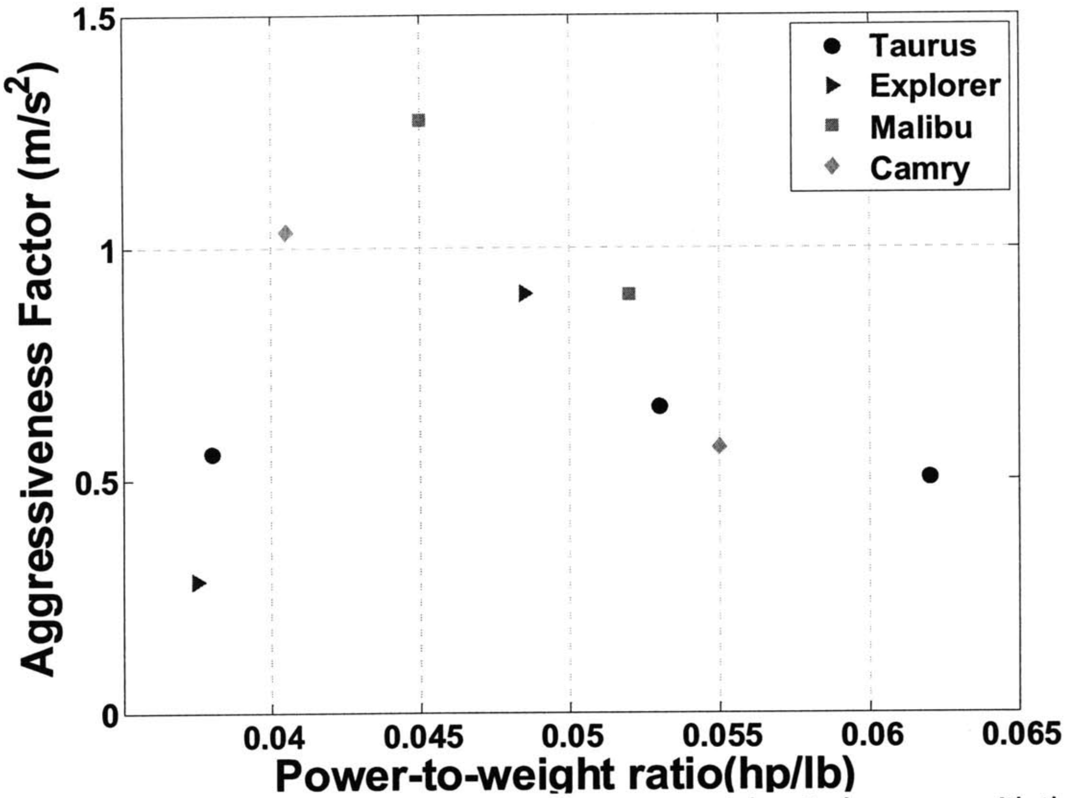

Figure 81: Aggressiveness factors versus power-to-weigh ratio by group, with the Taurus, Explorer, Malibu, and Camry groups identified separately

The finding of very low aggressiveness for low-performance vehicles is consistent with the conclusions of Johansson, Gustafsson, Henke, and Rosengren [2003]. They observed little differenc in the driving patterns of "eco-drivers" and normal drivers for a low-performance mid-size Toyota Corolla relative to a large, high performance premium class Volvo. They hypothesized that this was because higher interior engine noise in the Toyota than in the Volvo which encouraged drivers to avoid high engine noise. However, Andre et al. [2006] found only that high-powered cars showed significantly more aggressive driving than low-powered cars. They did not observe lower aggressiveness for very high performance vehicles. However, they separated low- and high-performance vehicles at 0.037 hp/lb which is lower than all of the vehicles in the 100-Car Study. Because of this, the conclusions of Andre et al. [2006] support the observations of this work. These aggressiveness trends imply that the higher shortfall observed for low-performance vehicles is due to the sensitivity of those vehicles to aggressiveness, not more aggressive driving. However, the trend of peaking aggressiveness at moderate vehicle performance seems to indicate that power-to-weight ratio is not the determining factor in aggressiveness, but may be an intermediate variable.

Examining the relationship between the average acceleration and average velocity distributions, shows us that velocity- and acceleration-scaling are reasonable methods to changes the aggressiveness of specific speed traces. As shown in Figure 82, there is no consistent trend between average positive acceleration and average velocity across the eleven vehicle groups. It is therefore fair to adjust each independently.

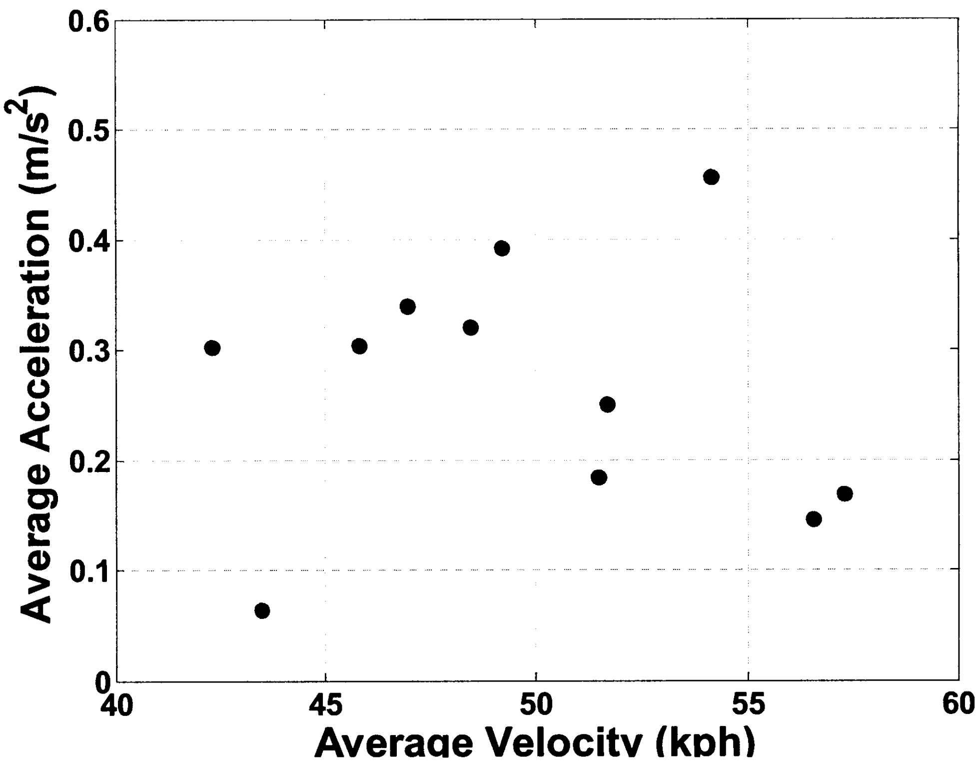

Figure 82: Average acceleration versus average velocity for the eleven groups

Fuel Savings from Changes in Velocity and Acceleration

Using 1) the accumulated data from all eleven vehicle groups as representative of the distribution of velocities and accelerations among real-world driving and 2) the aggressiveness factor calculations, fuel savings can be estimated for very simple changes in driving behavior. Reducing velocities during highway driving saves roughly the same amount of fuel as reducing accelerations during all driving by the same percentage. Although the average speed of the total driving is in the city driving range, where accelerations wheel work is proportional to fuel consumption, the velocities during highway driving impact fuel consumption as much as accelerations during all driving, because:

- Aggressiveness factors are distance-weighted,
- Aggressiveness factors are based on all driving, not just driving in the city speed band,
- The greatest distance is traveled in the highway speed band, and
- Higher speeds increase in wheel work much more than they increase average velocity.

As shown in Table 27, reducing velocities during highway driving by 10 percent using the method described in Chapter 3 (which reduces velocities without affecting the magnitude of accelerations) reduces the overall aggressiveness of the entire data set by 7 percent. For the Ford Focus this would equate to a 0.3 L/100km reduction in fuel consumption. Similarly, reducing all accelerations and decelerations by 10 percent without changing the vehicle velocity reduces aggressiveness by 6 percent and Focus fuel consumption by 0.2 L/100km. Reducing both highway speeds and accelerations and decelerations by 10 percent would reduce overall aggressiveness by 14 percent, or a 0.5 L/100km reduction in fuel consumption.

Table 27: Impact of reducing accelerations during all driving and velocities during highway driving, for the accumulated driving data, using the Ford Focus

	Percent Reduction	Reduction in Aggressiveness Magnitude (m/s^2)	Reduction in Aggressiveness Percent (%)	Reduction in Ford Focus Fuel Consumption* Magnitude (L/100km)	Reduction in Ford Focus Fuel Consumption* Percent (%)
Accel and Decels of All Driving	10	0.05	6.1	0.22	2.5
	20	0.10	12.3	0.44	5.0
Velocities of Highway Driving	10	0.06	7.3	0.26	3.0
	20	0.10	12.7	0.44	5.0
Both of the above	10	0.11	13.7	0.48	5.5
	20	0.21	26.1	0.91	10.5

*Based on the fit between fuel consumption and aggressiveness factor presented in Table 26

For individual groups, the fuel savings depend on the original, un-modified aggressiveness factor, as shown in Figure 83. For reducing velocities during highway driving: the lower the original aggressiveness factor, the greater the reduction in aggressiveness (and fuel consumption). For reductions in accelerations and decelerations: the higher the original aggressiveness factor, the greater the reduction in aggressiveness. For original, un-modified aggressiveness greater than 1.0 m/s^2, reducing accelerations and decelerations by 10 percent saves more fuel than reducing highway speeds by 10 percent. For aggressiveness factors below 0.6 m/s^2 the opposite is true. For example, for the group with the lowest original aggressiveness factor, 0.3 m/s^2, a 10 percent reduction in highway speeds saves seven times more fuel than a 10 percent reduction in acceleration and decelerations. For original aggressiveness factors between 0.6 m/s^2 and 1.0 m/s^2, both accelerations and highway speeds are effective. All of these effects are due to the fact that the average speed of each group falls in the city speed range, where fuel consumption is proportional to acceleration wheel work, and are consistent with the eco-driving literature. Barth and Boriboonsomsin [2009] showed that eco-driving, which focuses on accelerations and decelerations, is most effective under severely congested conditions. Although the Ford Explorer has a much higher aerodynamic drag and curb weight, for the two Explorer groups, both reducing highway speeds and accelerations and decelerations fit the trend of the entire eleven groups.

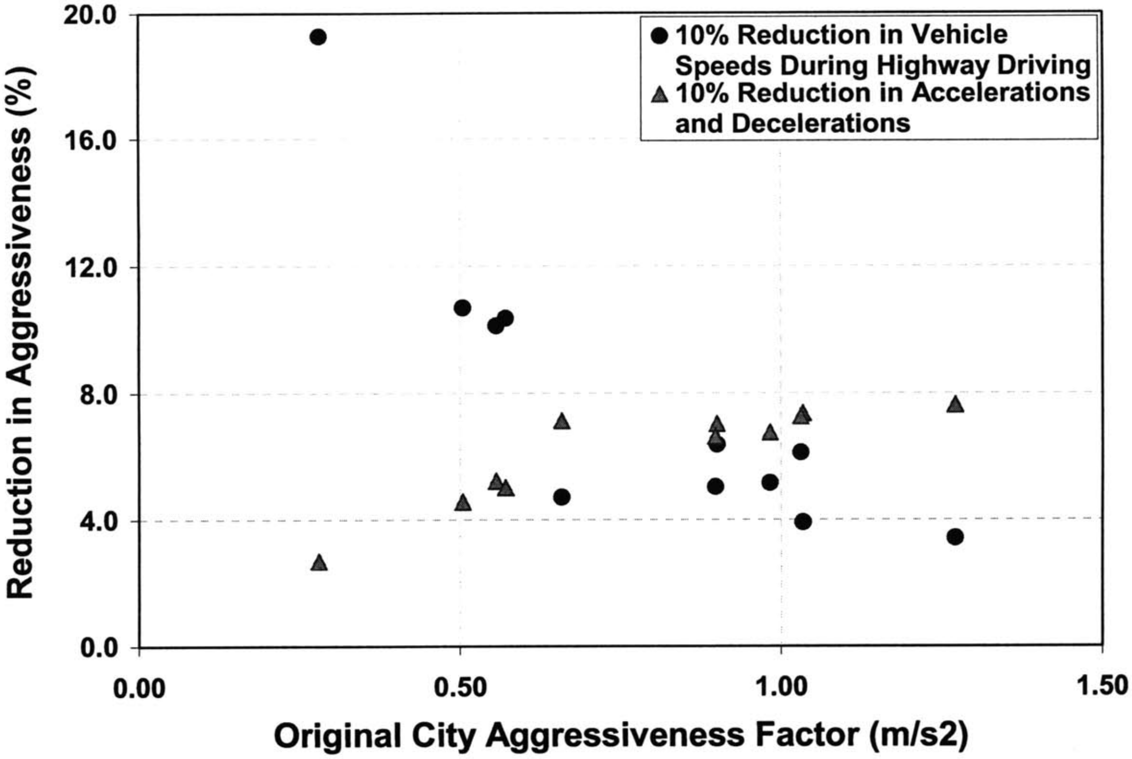

Figure 83: Reduction in aggressiveness factor for each of the vehicle groups due to a 10 percent reductions in highway speeds and a 10 percent reduction in accelerations

As percent reductions in accelerations increase, the percent reduction in aggressiveness increases linearly. And the lower the initial aggressiveness factor, the lower the proportional increase in aggressiveness. As a result, very large reductions in accelerations cause a wide range of reductions in aggressiveness. Figure 84 shows the range of reductions in aggressiveness due to percent reductions in accelerations. Group 1 had the lowest reductions, and group 5 had the highest reductions. A 20 percent decrease in accelerations and decelerations leads to between a 5 and 15 percent drop in aggressiveness. As shown in Table 27, for the accumulated data, this would be a 0.44 L/100km (5.0 percent) reduction in fuel consumption for a Ford Focus.

As with accelerations and decelerations, the impact of reducing velocities during highway driving is linked to the original aggressiveness factor; however, the impact is reversed. In addition, the trend is non-linear. The greater the percent reduction in vehicle velocities during highway driving, the greater the drop in aggressiveness. Figure 85 shows the range of reductions in aggressiveness due to reductions in highway speeds. Group 1, which has the lowest original aggressiveness, experiences dramatic reductions in aggressiveness; group 5, which has the highest original aggressiveness factor, experiences only moderate reductions in aggressiveness. For a 20 percent reduction in highway speeds, the change in aggressiveness is between 5 and 35 percent, corresponding to a 0.43 L/100km (4.7 percent) reduction in Focus fuel consumption for the accumulated data.

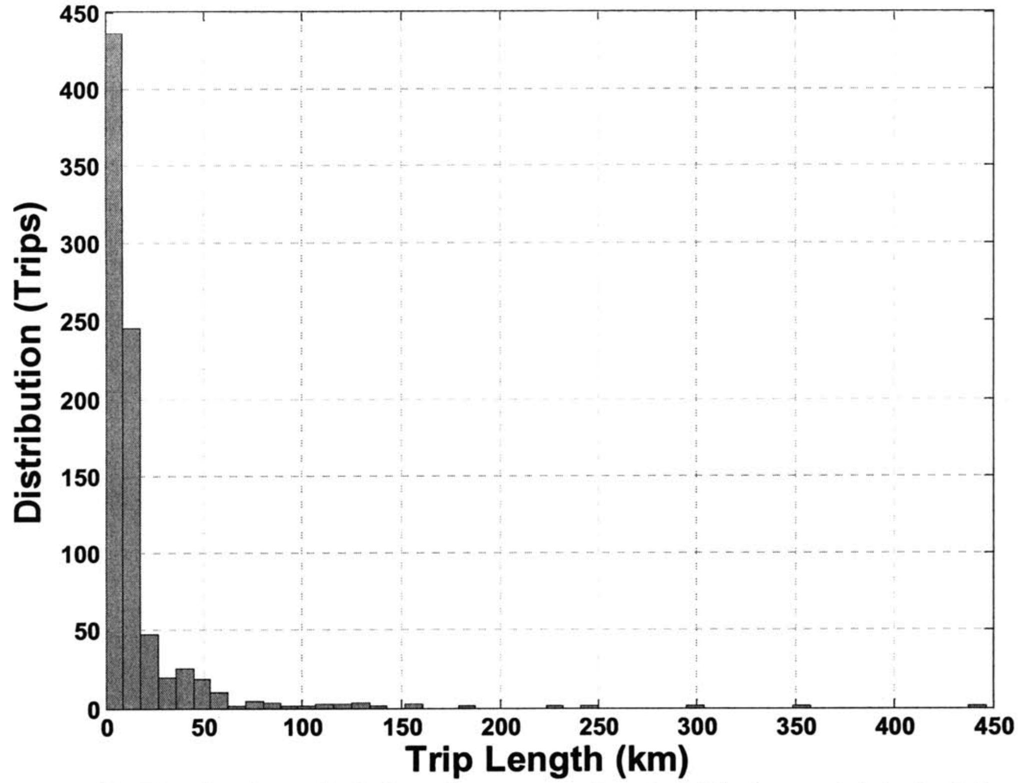

Figure 88: Distribution of trip lengths among the CarChip-logged data by trip

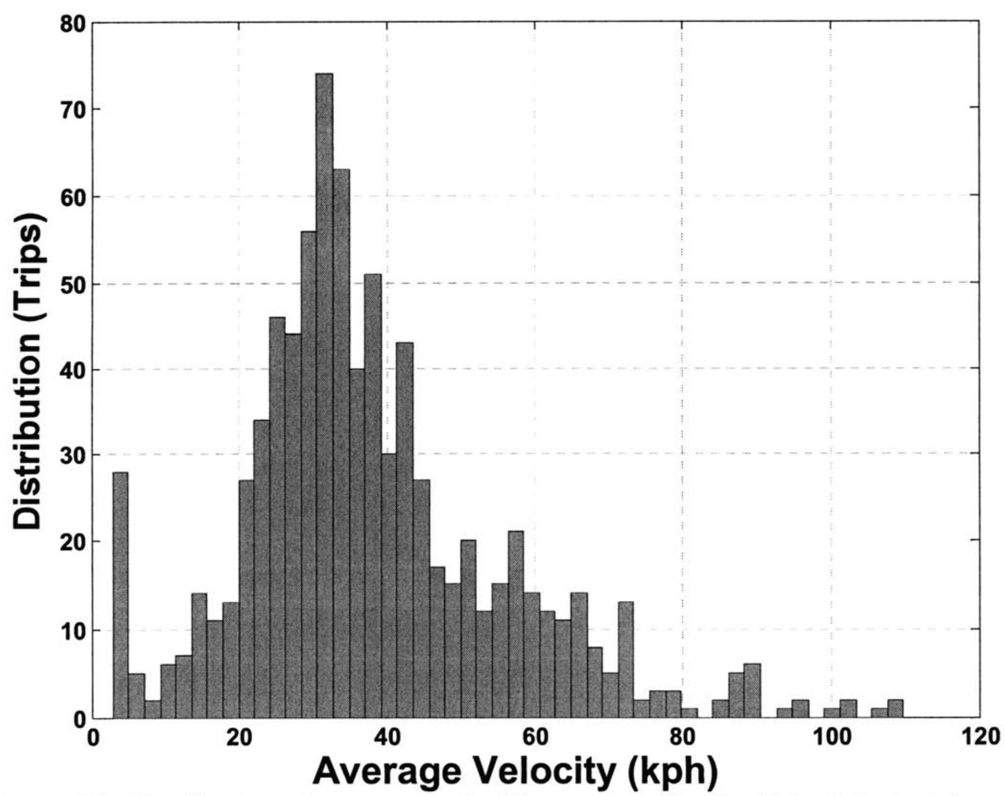

Figure 89: Distribution of average velocities among the CarChip data by trip

Because of the differences in how aggressiveness is affected by reductions in accelerations and in highway speeds, initially, highway speeds have a slightly larger impact. However, at higher percent reductions, accelerations and decelerations have a greater impact. This is reflected in Figure 86 which shows the percent reduction in aggressiveness (which is proportional to reductions in fuel consumption) for reductions both in accelerations and decelerations and in highway speeds.

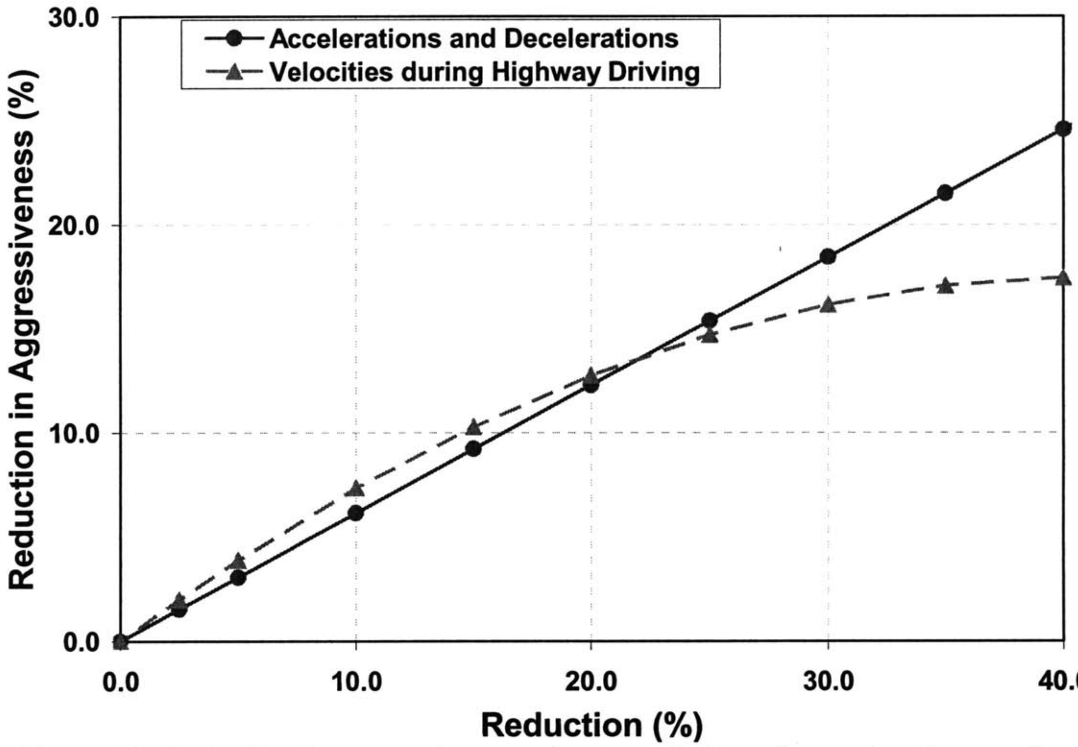

Figure 86: Reduction in aggressiveness due to reductions in accelerations and decelerations and in highway speeds

Reductions in accelerations and decelerations should not affect travel time. This is confirmed by the eco-driving literature, where accelerations and decelerations are the main focus. For example, Saynor [2008] reports significant fuel savings with either no reductions or increases in average speed. However, reductions in highway speeds increase travel time by linearly reducing overall average speed. The magnitude of this impact depends on the average speed and the percentage of driving that is at highway speeds. Figure 87 shows the percent reduction in average speed versus the percent reduction in highway speeds for the total driving data and for groups 1 and 2, the groups most and least sensitive to highway speeds. A 10 percent reduction in highway speeds reduces overall average speed (and increases overall travel time) by between 4 and 7 percent, while a 30 percent reduction in highway speeds increases travel time by between 13 and 21 percent.

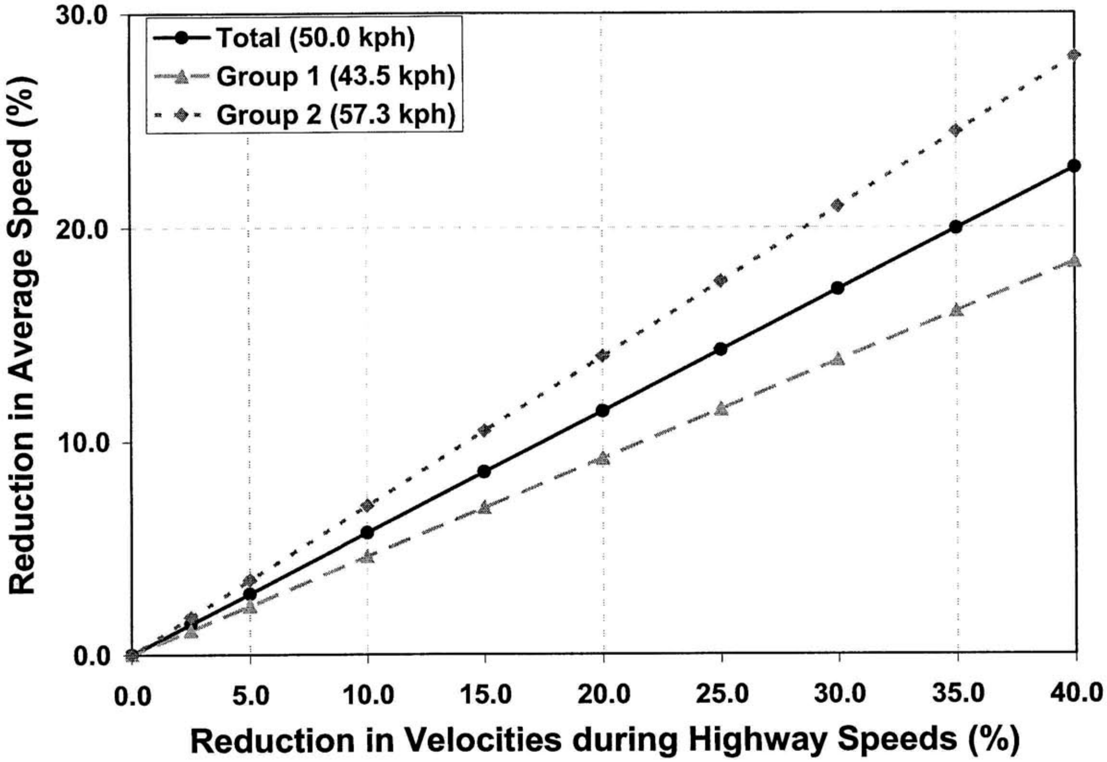

Figure 87: Reduction in average speed due to reductions in highway speeds

7.2 Driving in the CarChip Data

While less representative, the data collected using the CarChips provides information about the distribution of aggressiveness within trips, by speed, and by distance. A total of 824 trips covering a total of 12,620 km were collected from 15 different vehicles. This data is assessed by trip instead of by velocity and acceleration distributions.

Basic Analysis

The average length of the trips is 15 km (9.5 miles). This is slightly lower than the average length found in the 2001 National Household Travel Survey: 16 km (9.9 miles), which was up from 14.6 km in the 1995 survey and 14.3 km in 1990 [Hu and Reuscher, 2001]. As shown in Figure 88, a surprising proportion of trips were short distance. Of the total, 528 trips (64 percent) were less than 12 km (7.5 miles) and 316 trips (38 percent) were less than 5 km (3 miles).

The average speed of the trips is 52 kph (32 mph). As shown in Figure 89, the largest percentage of these trips (54 percent) fall into the city driving category, with average speeds between 32 and 72 kph. By trip, neighborhood driving is the second most common, representing 38 percent of all trips. And, surprisingly, 23 trips (almost 3 percent) have average speeds below 5 kph (3 mph). Finally, less than 5 percent of trips had average speeds above 72 kph.

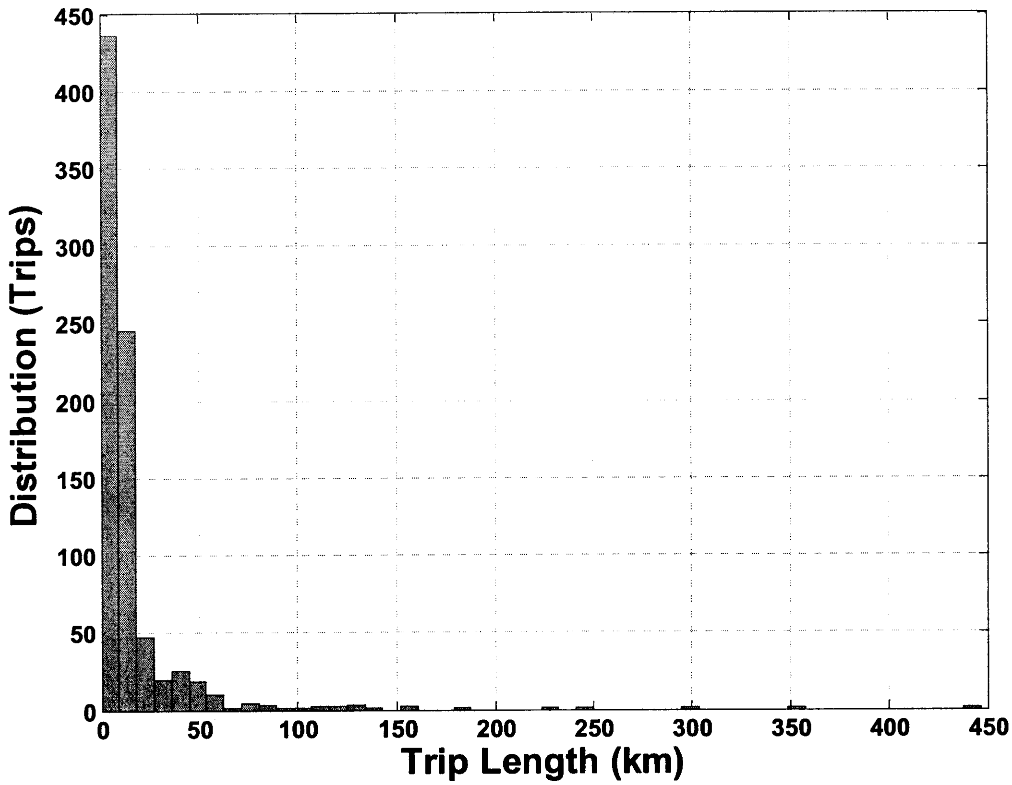

Figure 88: Distribution of trip lengths among the CarChip-logged data by trip

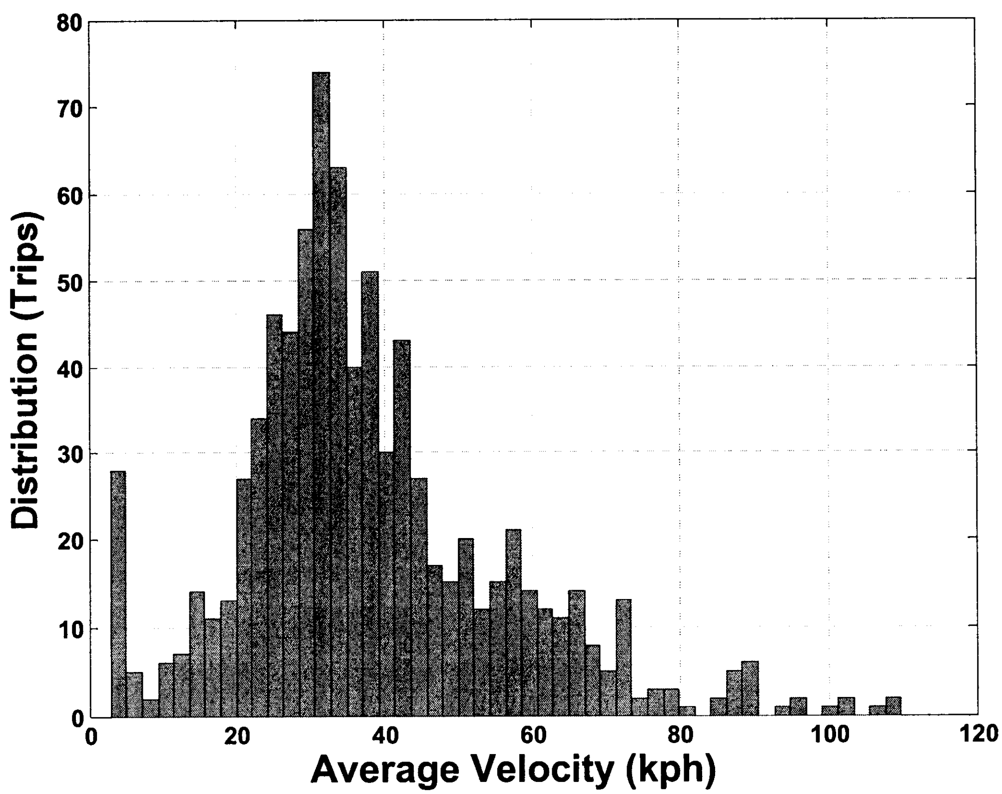

Figure 89: Distribution of average velocities among the CarChip data by trip

Longer trips tend to have higher average speed. Figure 90 shows average speed versus distance with 32 kph and 72 kph marked with horizontal slashed lines. All cycles longer than 20 km have average speed 32 kph or greater, and almost all cycles shorter than 2 km have average speed less than 32 kph.

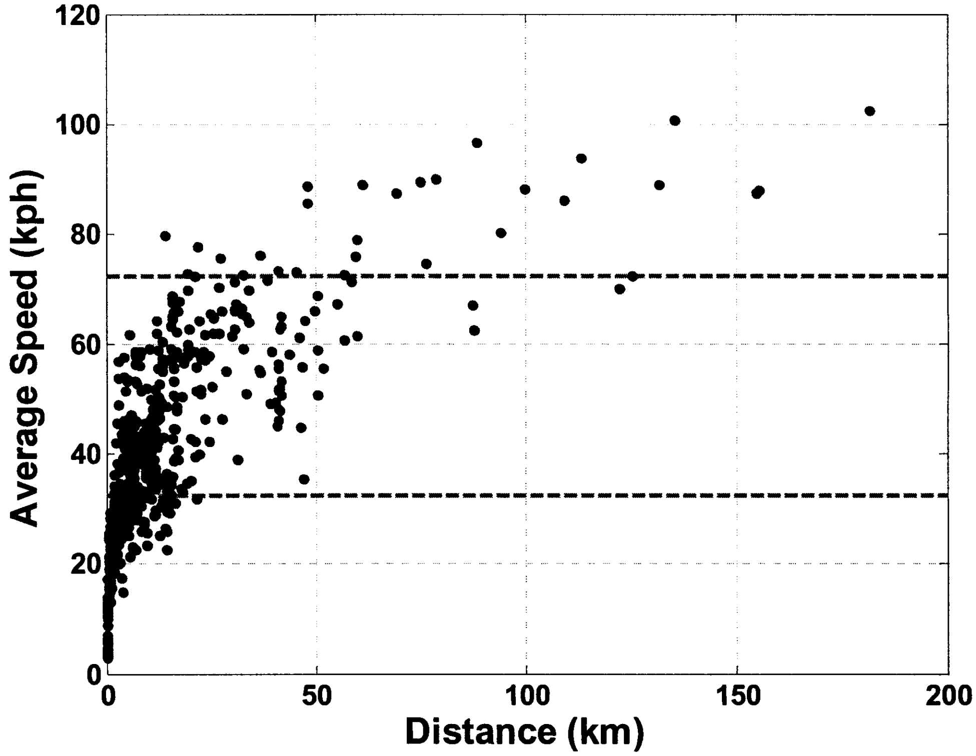

Figure 90: Average velocity versus trip distance

Aggressiveness

Aggressiveness factors for all of the CarChip driving patterns were calculated as if driven by the Ford Focus. The city aggressiveness factor for the entire 12,620 km of driving (average speed 52 kph) is 0.54 m/s^2. A Ford Focus driven over these trips would have a fuel consumption of 7.5 L/100km (fuel economy of 31.4 mpg). This is much lower than the average aggressiveness of the 100-Car driving data. (0.80 m/s^2). The CarChip trips can be separated into city, highway, and neighborhood trips.

City Driving Patterns

As mentioned above, 446 trips had average speed between 32 kph and 72 kph. The total distance of these city trips is 7,320 km. As shown in Figure 91 along with a lognormal fit, the distribution of aggressiveness factors by distance has a longer upper tail than lower tail, as with the 100-Car vehicle groups. The distribution of real-world fuel economy values has a similar shape [Saynor, 2008]. By distance, the average city aggressiveness factor is 0.42 m/s^2 with a standard deviation of 0.10 m/s^2. The highest aggressiveness factor observed is 0.87 m/s^2.

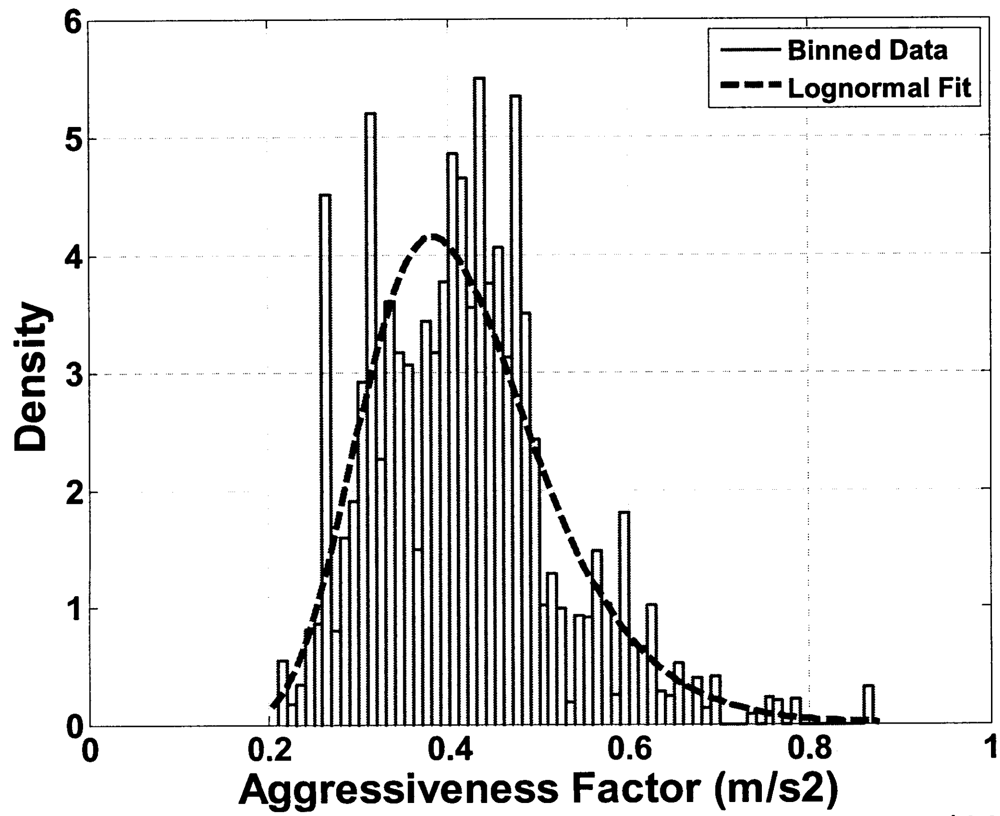

Figure 91: Distribution of aggressiveness factors by distance among city driving patterns

Highway Driving Patterns

The 38 trips with average speed above 72 kph sum to 3,950 km. By distance, the average aggressiveness is 0.55 m/s^2 with a standard deviation of 0.13 m/s^2. As shown in Figure 92, the distribution of highway aggressiveness factors falls between the aggressiveness of the HWFET drive cycle (0.22 m/s^2) and the US06 drive cycle (0.81 m/s^2). There is not enough data to fit a distribution.

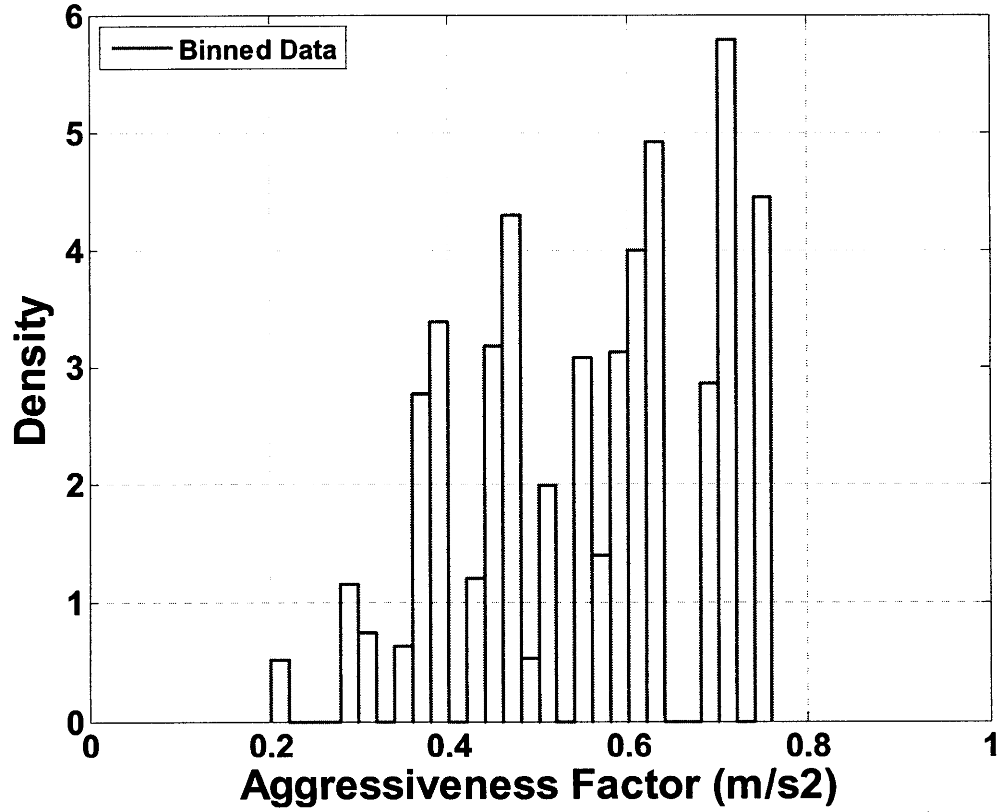

Figure 92: Distribution of aggressiveness factors by distance among highway driving

Neighborhood Driving Patterns

Summing the neighborhood driving trips comes to just 1,350 km. As shown in Figure 93, the distribution of aggressiveness factors for neighborhood driving, along with a lognormal fit, has a very long upper tail. The average aggressiveness factor by distance is 1.35 m/s^2 with a standard deviation of 0.78 m/s^2. To put this in perspective, the aggressiveness factor of the FTP drive cycle is 1.54 m/s^2. Another feature of neighborhood driving is that aggressiveness increases with decreasing trip distance, as shown in Figure 94. For trips less than 2 km, aggressiveness increases even more dramatically.

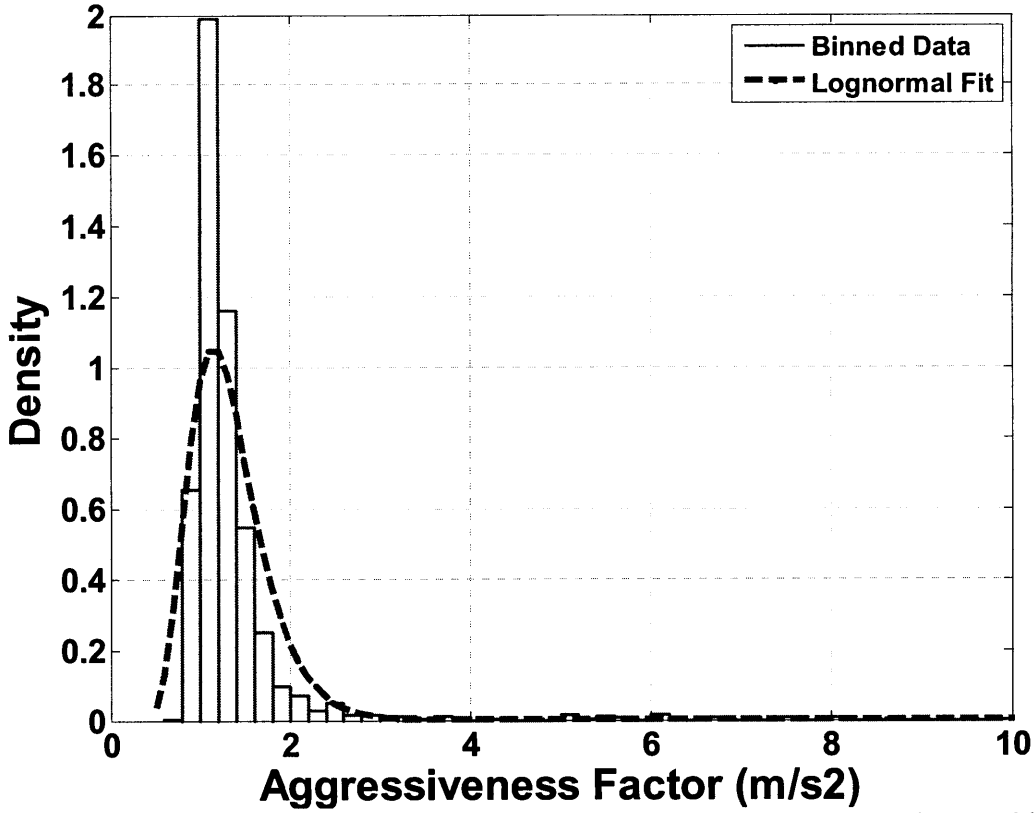

Figure 93: Distribution of aggressiveness factors by distance among the neighborhood driving patterns

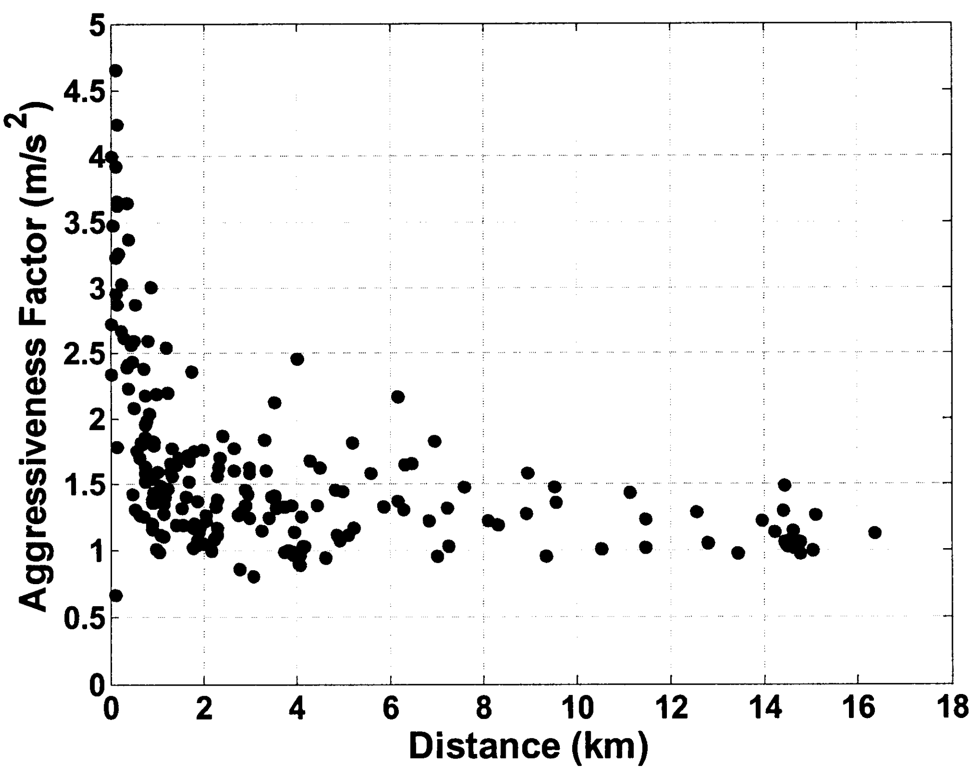

Figure 94: Aggressiveness factor versus distance for neighborhood driving trips

Fuel Savings from Changes in Aggressiveness

Another approach for estimating fuel savings is to use the distribution of aggressiveness factors. The result rests upon the linear relationship between aggressiveness factor and fuel consumption. The CarChip city driving, shown in Figure 95 with a normal distribution and two modified normal distributions, serves as an illustrative example. The standard deviation of the original distribution is 0.10 m/s^2. When a shift in average aggressiveness is accompanied by a reduction in this variability, the minimum aggressiveness remains the same. The impact of reducing the average aggressiveness in this way is summarized in Table 28. Shifting the distribution by one standard deviation (0.10 m/s^2 or 23 percent) would reduce fuel consumption by 0.42 L/100km or 5.6 percent for the Ford Focus. However, as shown above, a reduction in aggressiveness of this magnitude would require significant reductions in accelerations and decelerations or in velocities of highway driving.

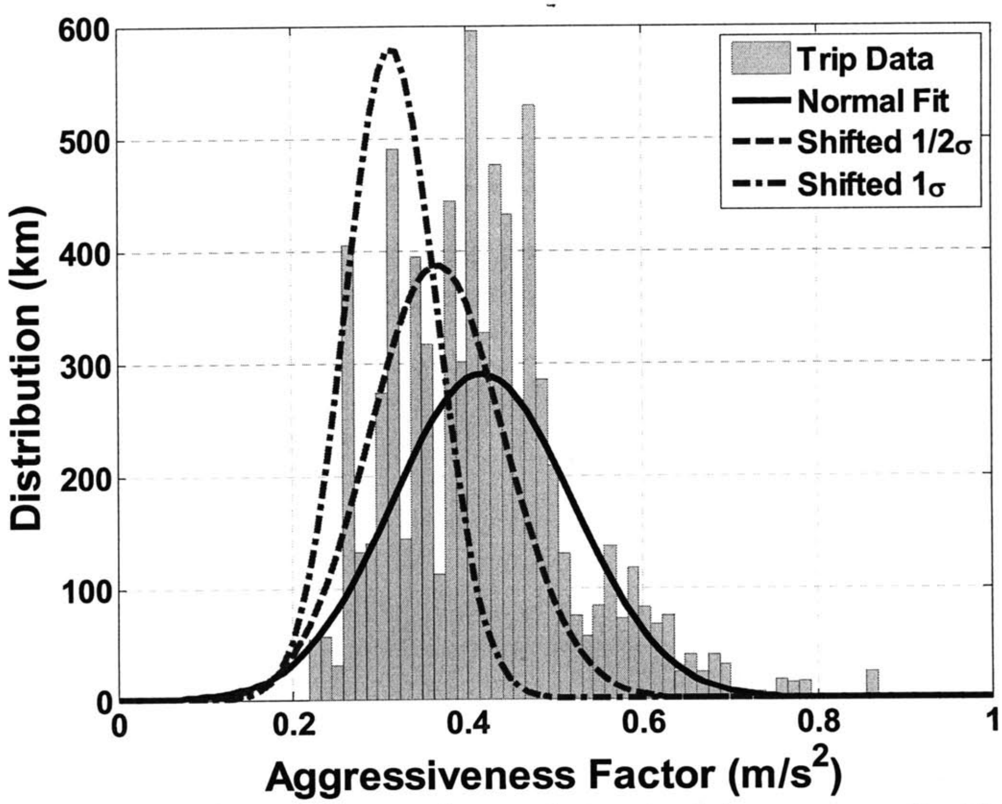

Figure 95: Distribution of aggressiveness factors by distance among city driving patterns with a normal fit and two shifted normal fit

Table 28: Approximate reductions in fuel consumption from reductions in aggressiveness for the distribution of city driving patterns

Shift in Aggressiveness Distribution (m/s^2)	Reduction in Fuel Consumption of the Ford Focus (L/100km)	Reduction in Fuel Consumption of the Ford Focus (%)
0.05	0.21	2.8
0.10	0.42	5.6
0.15	0.63	8.3
0.20	0.84	11.1

8 Conclusions

This section reviews and summarizes the primary findings of this work and develops them into tips for drivers. It then recommends three policy actions.

8.1 Findings

The findings of this work relate to the effects of driving style on the fuel consumption of conventional light-duty vehicles, the aggressiveness of real-world driving, and the potential for changes in driving style to reduce fuel consumption.

Driving Style and Fuel Consumption

The main conclusions about the relationship between driving style and fuel consumption of a conventional vehicle are that:

1. Fuel consumption can be explained by examining the wheel work and vehicle efficiency of a specific speed trace. The wheel work is the energy required at the wheels per unit distance, representing the "efficiency" of the driving pattern at traveling distance. The vehicle efficiency is the efficiency of the vehicle at using liquid fuel to deliver energy to the wheels. Together, they explain fuel consumption.

2. Fuel consumption is lowest during steady-speed driving at a moderate speed and increases with both increasing and decreasing speeds. As speed drops, vehicle efficiency decreases much more than wheel work. As speed increases, wheel work increases, while efficiency remains relatively constant.

3. The sensitivity of fuel consumption to aggressive driving depends upon how wheel work and efficiency change over a range of driving styles. Design changes that increase average efficiency, but make efficiency more consistent across a range of driving conditions increase the sensitivity of fuel consumption to aggressive driving. For conventional vehicles, such design changes include lower power-to-weight ratios and higher number of gears.

4. For transient driving, driving behaviors (accelerations and velocities), wheel work, efficiency, and fuel consumption behave differently in each of three speed bands. The average speed of a driving pattern determines which band it falls into; these speed bands are loosely defined as:

    - *Low speed/neighborhood driving*: average speeds below 20 mph (32 kph)
    - *Moderate speed/city driving:* average speeds between 20 and 45 mph (32 and 72 kph)
    - *High speed/highway driving:* average speeds above 45 mph (72 kph)

5. Within each speed band, because of the way that accelerations and velocities impact wheel work and efficiency:

   In low speed/neighborhood driving
   - Accelerations increase fuel consumption, but so do reductions in average speed. This is because, when acceleration increases, wheel work increases more than efficiency; and when speed decreases, efficiency decreases more than wheel work.
   - Average speed dominates since, in addition to increasing fuel consumption, it also increases the sensitivity of fuel consumption to accelerations.

   In moderate speed/city driving:
   - Accelerations dominate fuel consumption, and velocities have little effect. The reason is that, when speed increases, efficiency and wheel work increase roughly proportionally; while, when acceleration increases, wheel work increases more than efficiency.

   In high speed/highway driving:
   - Both accelerations and higher velocities increase fuel consumption, but higher velocities have the greatest impact. This is because, for both increasing speeds and increasing accelerations, wheel work increases dramatically, while efficiency changes only marginally. However, when speed increases, so does the sensitivity of wheel work to accelerations.

   However, in all three driving modes, it is the overall aggressiveness of the entire driving pattern, not the instantaneous behaviors, that is important for fuel consumption.

6. Within each of these three speed bands, the aggressiveness of driving can be quantified based on the wheel work and average speed of the driving pattern. Although defined differently for each speed band, all three aggressiveness factors are weight-normalized, distance-weighted metrics that are proportional to fuel consumption.

7. The aggressiveness factors can be used to
   - Compare drive cycles from around the world,
   - Assess the aggressiveness of real-world driving,
   - Determine the role of driving style in the fuel economy shortfall, and
   - Assess the effectiveness of eco-driving training, among other uses

Real-World Driving

Although not representative of "average" driving, some conclusions can be reached based on the two sets of real-world driving data that were analyzed:

1. The average speed of both driving sets is approximately 50 kph (32 mph), falling within the city speed band, where accelerations dominate fuel consumption. However, the greatest distance is traveled at highway speeds.

2. For both data sets, the aggressiveness of real-world driving falls above that of the original EPA city and highway cycles that were developed in the 70s. For the 100-Car Study, average aggressiveness is near that of the more aggressive, 90s drive cycles such as the US06 and LA92. For the CarChip-logged data, average aggressiveness is between the original drive cycles and the 90s drive cycles.

3. Based on the CarChip data, short trips at low speeds tend to have very high aggressiveness factors. This is because 1) high accelerations are more common at low speeds and 2) average velocity decreases with decreasing trip length. Trips of less than 5 km represent a relatively high percentage of trips (roughly 40 percent).

4. Based on the 100-Car Study, the driving patterns of very low performance vehicles exhibit the lowest aggressiveness. The driving patterns of mid-performance vehicles, the most common type of vehicle, exhibit the highest aggressiveness factors.

Fuel Saving

Based on the two real-world driving sets, the relationship between driving and fuel consumption, and basic assumptions about how drivers might reduce 1) accelerations of all driving and 2) speeds of highway driving.

1. For the accumulated data from the 100-Car Study, reducing velocities during highway driving saves roughly the same amount of fuel as reducing accelerations during all driving by the same percentage. Assuming a fleet of Ford Focuses, a 20 percent reduction in either all accelerations or all highway speeds would reduce total fuel consumption by approximately 5 percent.

2. For individual vehicles, the effectiveness of specific driving behaviors at reducing fuel consumption varies significantly. Specifically, the original aggressiveness of a driving pattern affects which method (lower accelerations or lower speeds during highway driving) will be most effective at saving fuel:
   - Very aggressive drivers can save the most fuel by using lower accelerations,
   - Very un-aggressive drivers can save the most fuel by using lower velocities during highway driving,
   - Moderately aggressive drivers can save fuel equally by using lower accelerations and by using lower velocities during highway driving.

   This is because, for accumulated driving, accelerations have the largest impact on fuel consumption, so driving patterns with low aggressiveness have low original accelerations.

3. Although low performance vehicles are most sensitive to changes in driving aggressiveness, moderate performance vehicles, those with the most common power-to-weight ratios, offer the greatest potential for fuel savings due to the combination of:
   - High original aggressiveness and
   - Moderate sensitivity to aggressiveness.

8.2 Tips for Lower Fuel Consumption

Although this work has evaluated total driving, including environmental effects, and does not attempt to separate between environmental and driver effects, the findings can be used to develop tips for individual drivers. Based on how driving style affects fuel consumption and real-world driving, individual drivers should aim to:

1. Drive at lower highway speeds, but not lower neighborhood or city speeds;

2. Use lower accelerations during all driving, but particularly during low and moderate speed driving; and

3. Eliminate short, low speed trips as much as possible

Based on original, un-modified aggressiveness:

4. Drivers with low original aggressiveness should: focus on reducing accelerations and decelerations over reducing speeds during highway driving.

5. Drivers with high original aggressiveness should: focus on reducing speeds during highway driving over reducing accelerations and decelerations.

Additional tips from the literature, not specifically examined here, include:

6. For manual transmissions, use the highest gear possible

7. Eliminate excessive idling

8. Combine trips to reduce overall distance traveled

9. Don't wait for the engine to warm-up before driving

10. Use cruise control, except for on hills

11. Keep tire pressure high

12. Don't use a roof rack or other parts that increase aerodynamic drag

13. Remove excess weight

14. Use air conditioning and other accessories only when necessary

8.3 Recommendations

This work has explained how driving style affects the fuel consumption of conventional vehicles and has evaluated the aggressiveness of real-world driving. It has demonstrated the potential for fuel savings and offered advise on how to save fuel through driving style. However, to achieve these reductions, action is necessary. There are many options for attempting to change driving style, as described by Barkenbus [2009]. This work has not attempted to assess these, but does recommend two distinct actions:

1. Driver education programs and
2. Promotion of in-vehicle feedback

However, these actions must be part of a larger, coordinated policy effort.

Driver Education

As discussed in Chapter 2, eco-driving programs in Europe have been effective in achieving real-world fuel savings. In the U.S., promotion of more efficient driving has largely been limited to efforts by automotive companies and state governments. To be most effective, driver education programs should include both driver training and public information campaigns. In addition to informing drivers about tips for more efficient driving, such education programs should focus on:

1. Directing tips toward mainstream drivers,
2. Addressing misconceptions about driving, and
3. Motivating more efficient driving styles.

First, as shown above, the drivers of vehicles with moderate power-to-weight ratios, the most common vehicles, stand to save the most fuel through changes in driving style. Vehicles with moderate power-to-weight ratios have the most aggressive driving patterns and are more sensitive to aggressiveness than higher performance vehicles. Lower performance vehicles are even more sensitive, but have lower potential for less aggressive driving. Second, as demonstrated repeatedly in the literature, there are misconceptions over the relationship between fuel economy, fuel use, and specific driving behaviors. For example, on average, drivers overestimate the time saved by going faster on the highway [Fuller et al., 2009] and underestimate both their average speed [Walton and McKeown, 2001] and the effects of speed on safety [Mannering, 2009]. Addressing these misconceptions could go a long way toward encouraging more efficient driving. Finally, Johansson, Gustafsson, Henke, and Rosengren [2003] showed that both training and motivation are needed for drivers to achieve long-term fuel savings. One way for education programs to do this is to promote the link between personal vehicle fuel consumption and climate change [DeCicco, 2006].

In-Vehicle Feedback

Real-time, in-vehicle feedback systems reduce fuel consumption by 1) addressing accelerations and highway speeds and 2) increasing the effectiveness of driver education programs. Barth and Boriboonsomsin [2009] found that providing real-time in-vehicle driving advice could reduce fuel consumption by 10 to 20 percent. Additionally, displaying vehicle speed on a scale proportional to the square of speed, decreases the average speed of fast drivers by 3 percent [Yamada et al., 2006]. Devices that encourage more efficient driving are becoming increasingly common in new vehicles. Recent designs include the Ford "SmartGauge," Honda Ecological Drive Assist (Eco Assist), Fiat eco:Drive software, and Eco-Drive service of the Nissan Carwings system [Calem, 2009]. Add-on devices for existing vehicles include the Garmin EcoRoute [Garmin, 2010], ScanGaugeII, and the HKS CAMP system [Allen, 2008]. The main advantages of in-vehicle feedback system are that they provide:

1. Accurate fuel consumption measurements,
2. Real-time motivation and reminder to drivers, and
3. Targeted driving advise

Greene [2008] argued that we need "more accurate predictions for individuals not less biased estimates for the average driver," encouraging the use of fuel economy gauges and internet-based fuel economy predictions. An alternative way to do this, recommended by Andre et al. [2006], would be to have different drive cycles for different vehicles, based on the power-to-weight ratio of the vehicle. However, there is much to support using standardized drive cycles. As early as 1981, Car and Driver observed that, because they provided a standardized way to compare vehicle fuel economy, the fuel economy labels on new cars were the "the most important part of any new car" [Pirkey, McNutt, Hemphill, and Dulla, 1982]. In-vehicle feedback is a better option for providing more accurate fuel consumption information. Further support for these systems comes from the literature. Based on repeated studies, the long-term effect of eco-driving training is magnified by continuous feedback. For example, based on a review of all studies presented at the 2007 ITF Workshop on Eco-driving, eco-driving training can reduce long-term fuel consumption by 5 percent without feedback and by 10 percent with continuous feedback [Onoda, 2009]. Finally, as presented here, the effectiveness of specific driving behaviors at reducing fuel consumption depends on the original aggressiveness factor. In-vehicle advisory systems could provide tailored advise based on the existing driving style. For example, encouraging very aggressive drivers to focus on reducing accelerations.

Coordinated Policy Effort

Driving style and travel behavior are "embedded in a web of other behaviors and decisions" [ITF, 2008]. For example, driving patterns are influenced by the driver, vehicle, weather, time of year, time of day, speed limits, type of roadway, street function, density of junctions, and traffic conditions, among other factors. Because of these complexities, policies that attempt to change driving behavior could have unintended consequences for other aspects of vehicle use. Policies directed at encouraging more efficient driving must be part of a larger, coordinated policy effort such as that proposed by Heywood et al. [2009].

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Appendices

Appendix A: Standard Drive Cycles

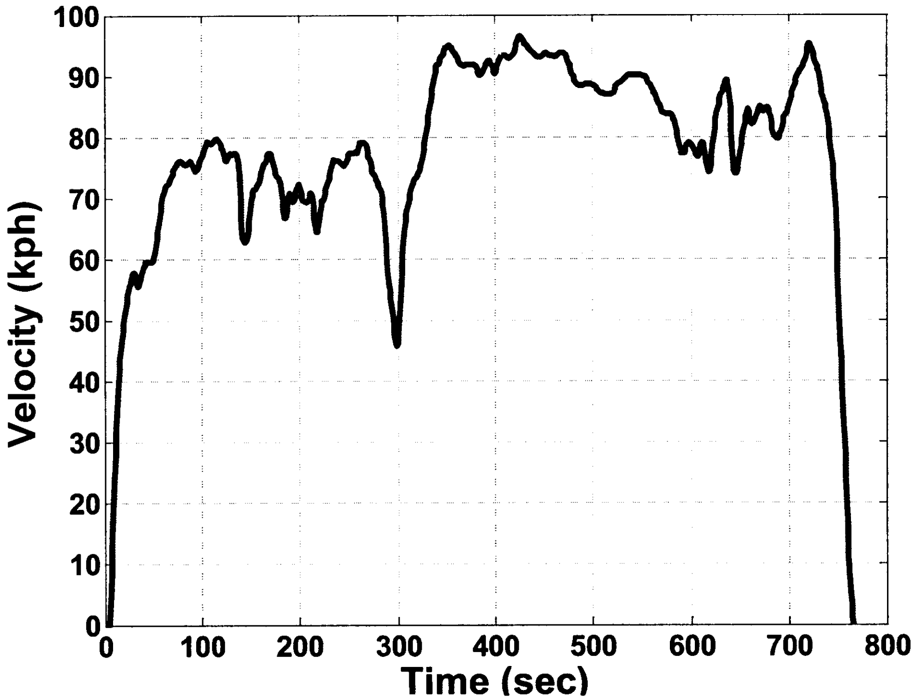

Figure 96: The Highway Fuel Economy Test (HWFET) drive cycle

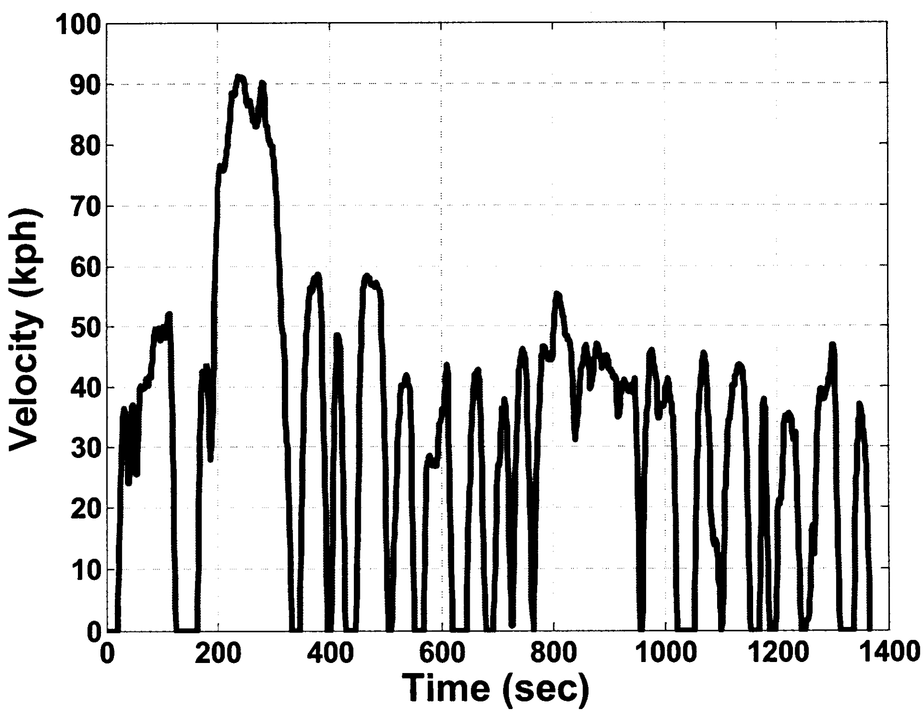

Figure 97: The Federal Test Procedure (FTP) drive cycle

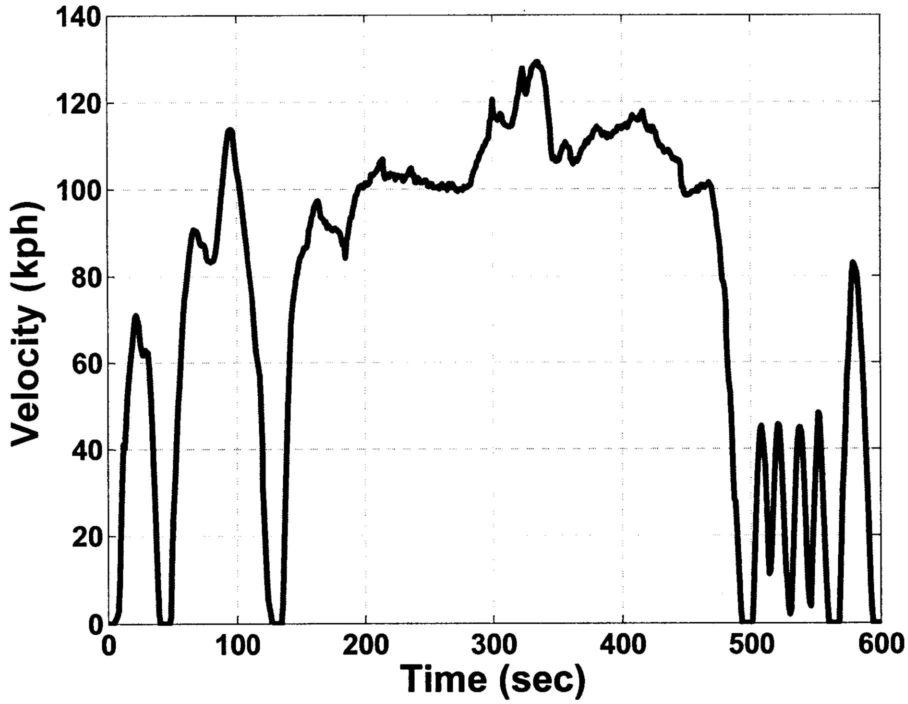

Figure 98: The US06 drive cycle

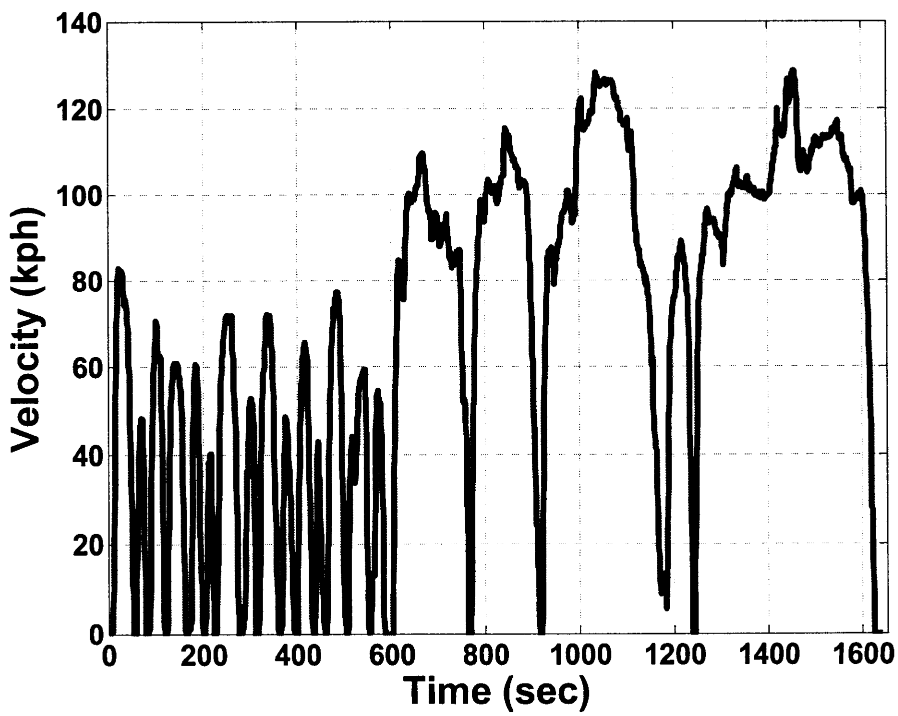

Figure 99: The Air Resources Board drive cycle No.2 (ARB02)

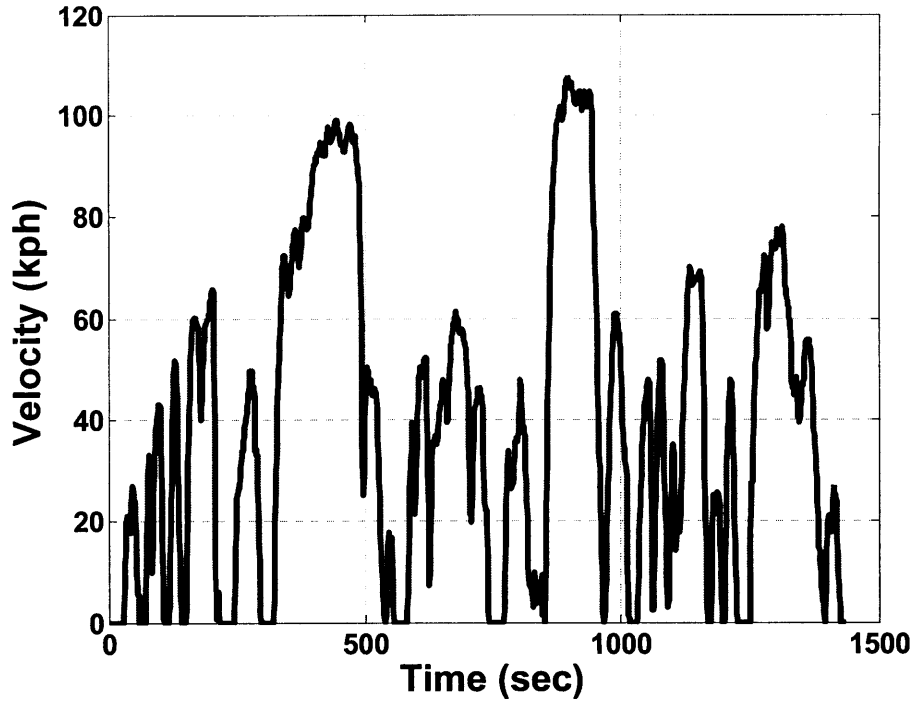

Figure 100: The LA92 drive cycle

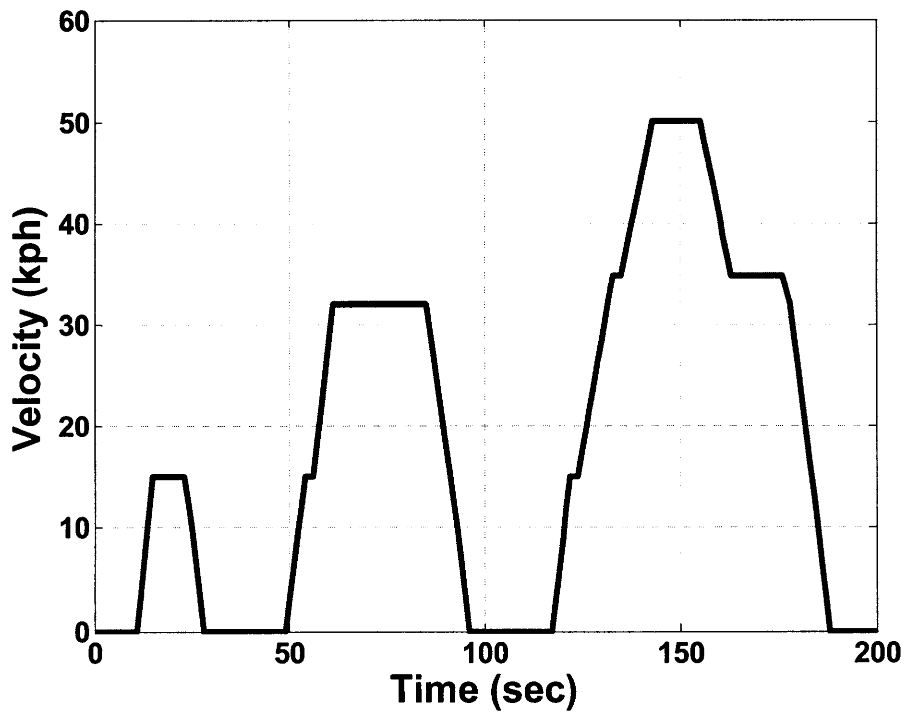

Figure 101: The Economic Commission of Europe (ECE) drive cycle

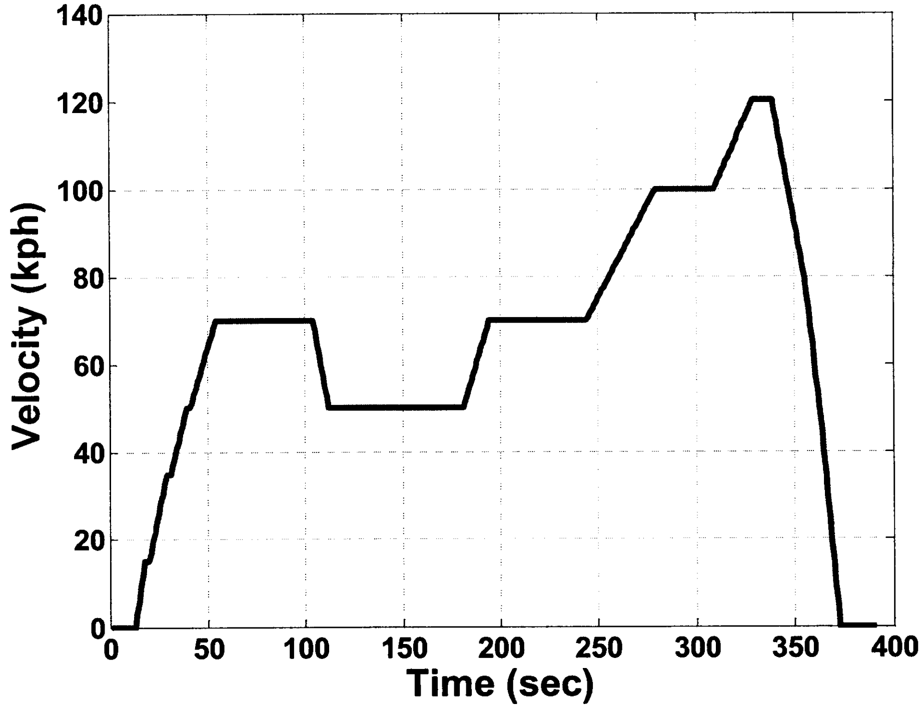

Figure 102: The Extra Urban Driving Cycle (EUDC) drive cycle

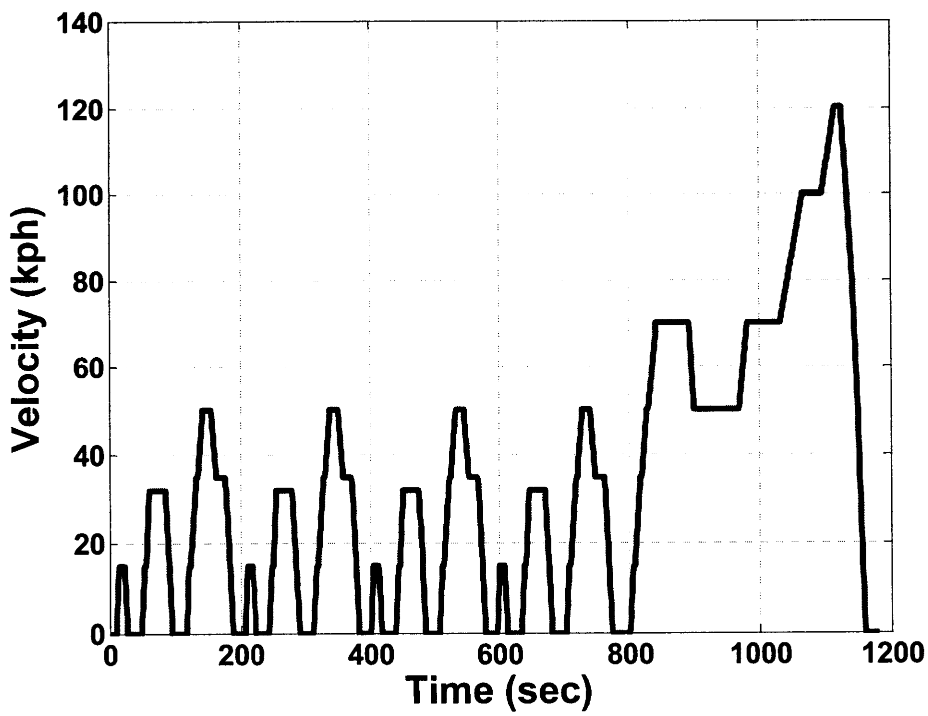

Figure 103: The New European Drive Cycle (NEDC) drive cycle

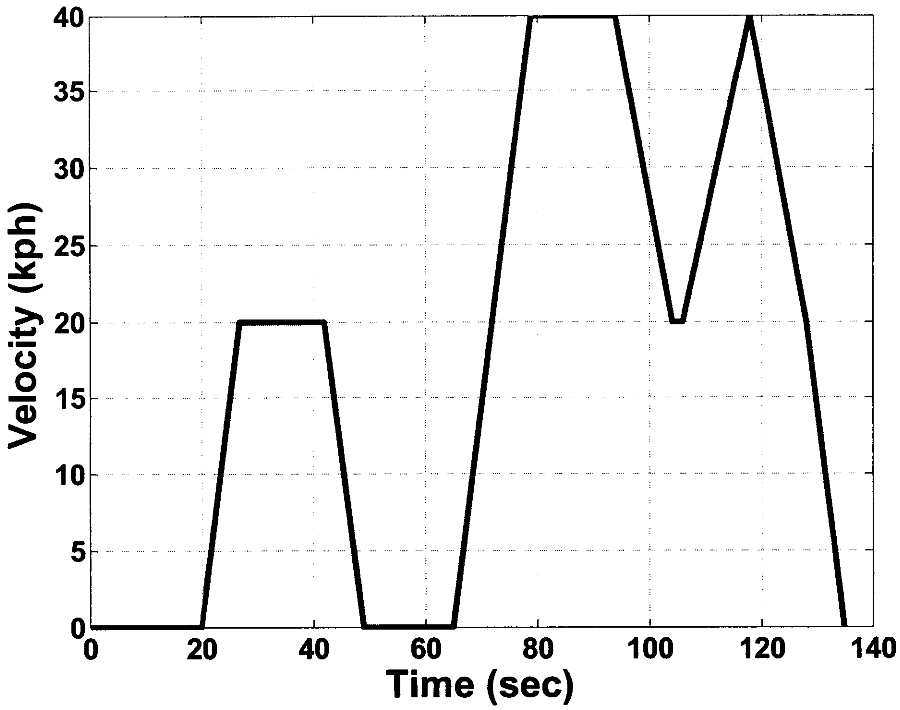

Figure 104: The Japan 10 mode drive cycle

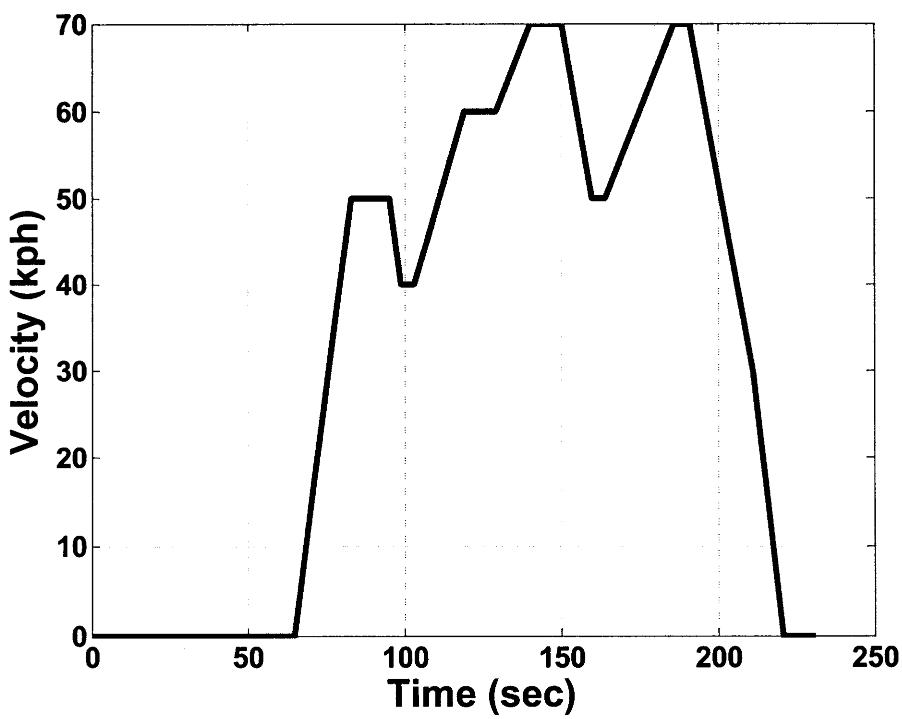

Figure 105: The Japan 15 mode drive cycle

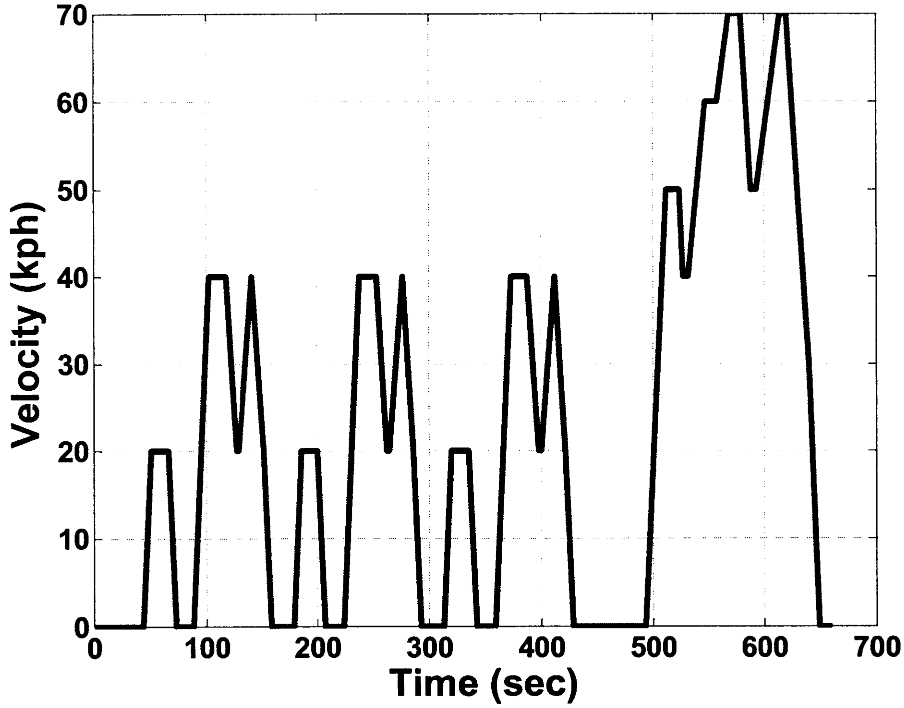

Figure 106: The Japan 10/15 mode drive cycle

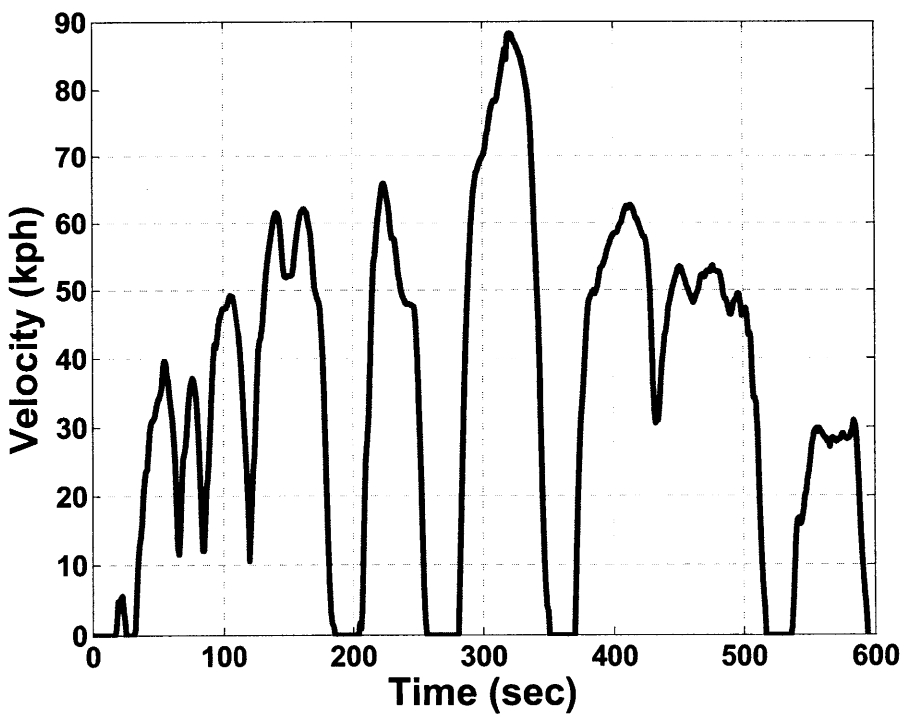

Figure 107: The U.S. EPA air conditioning drive cycle (SC03)

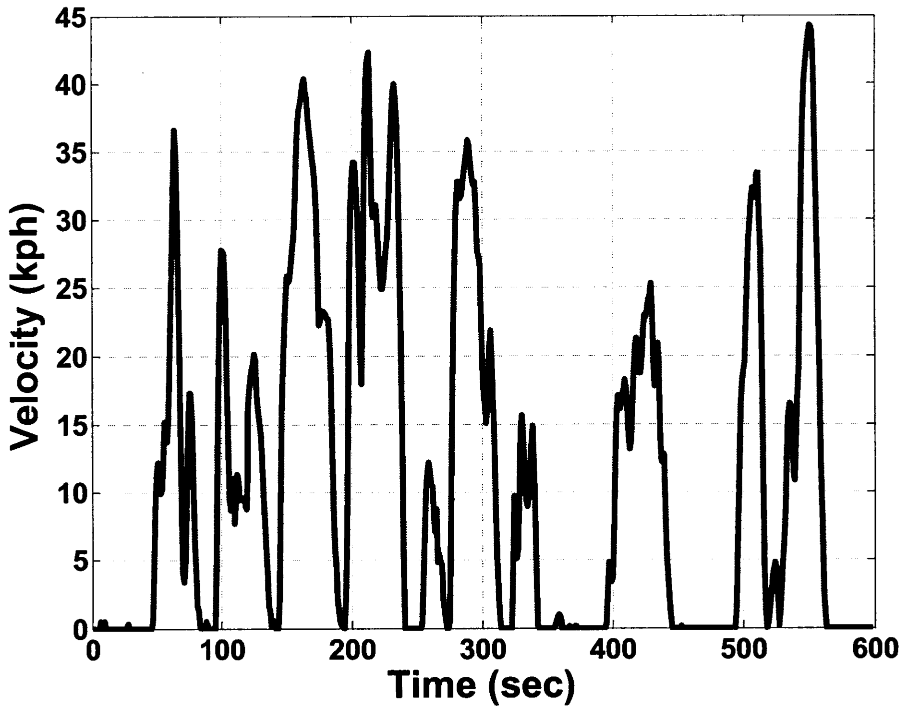

Figure 108: The NY City Traffic drive cycle

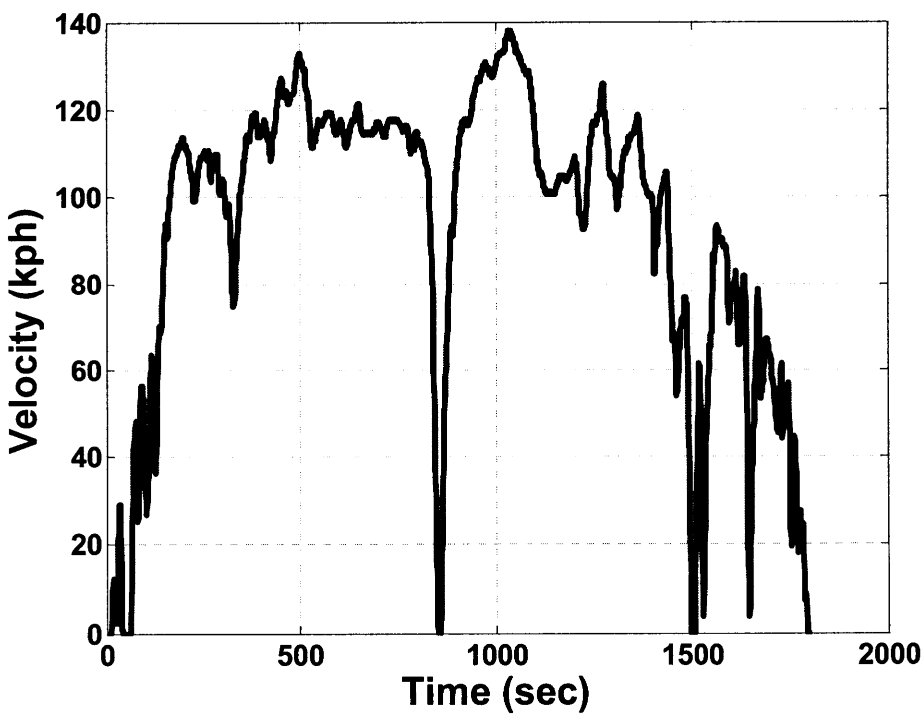

Figure 109: The INRETS highway drive cycle

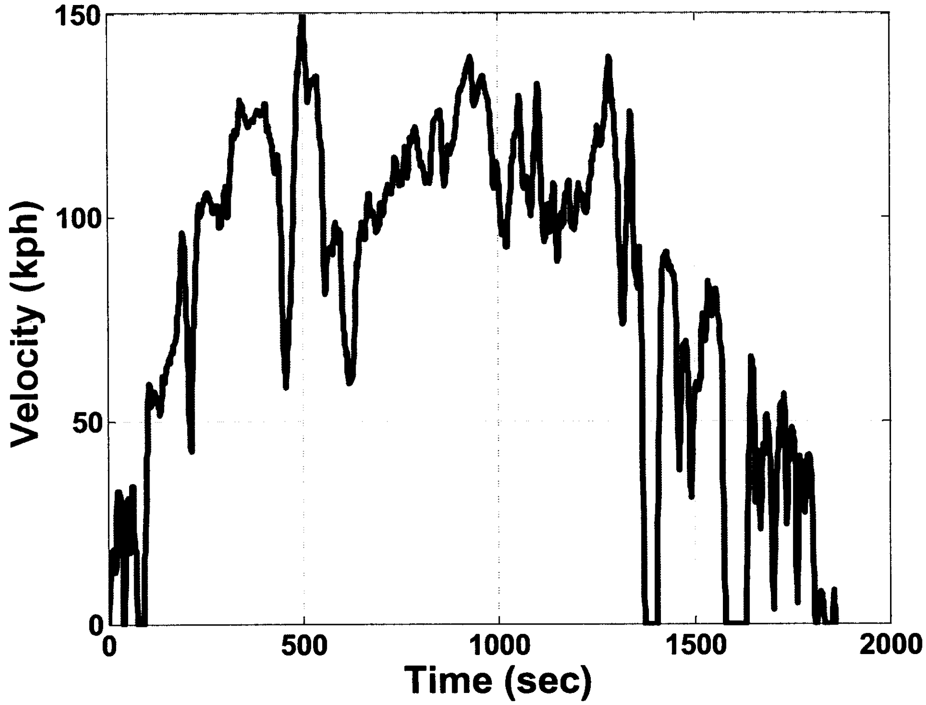

Figure 110: The INRETS highway1 drive cycle

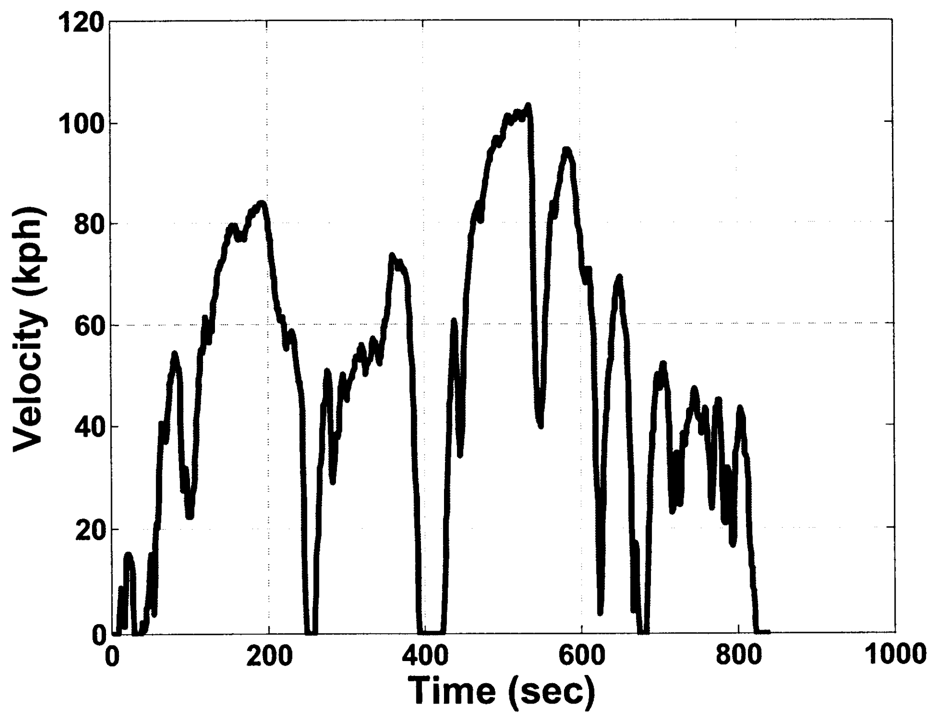

Figure 111: The INRETS road drive cycle

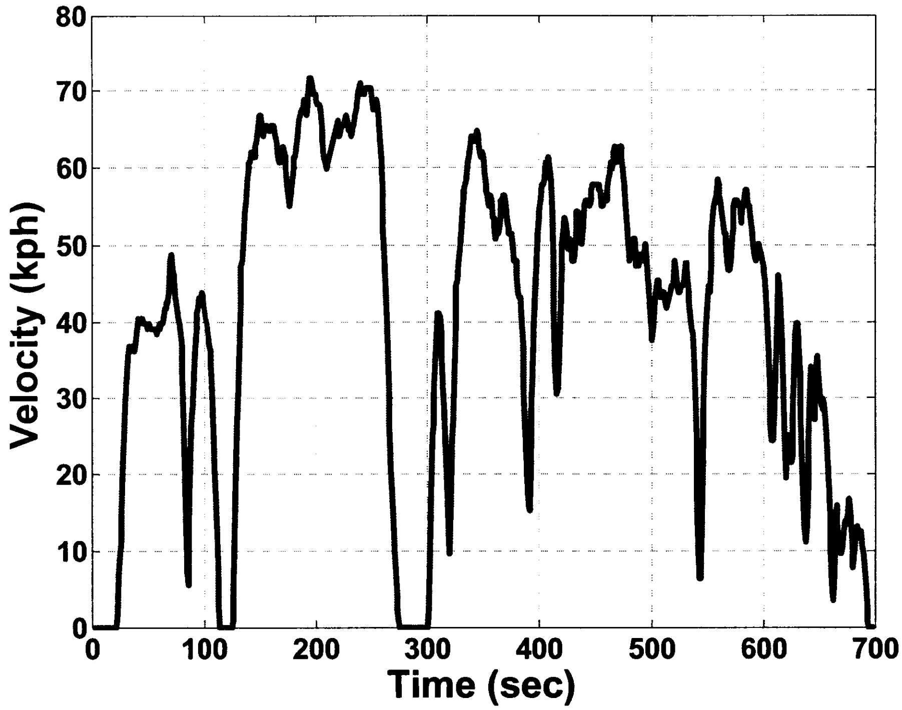

Figure 112: The INRETS road1 drive cycle

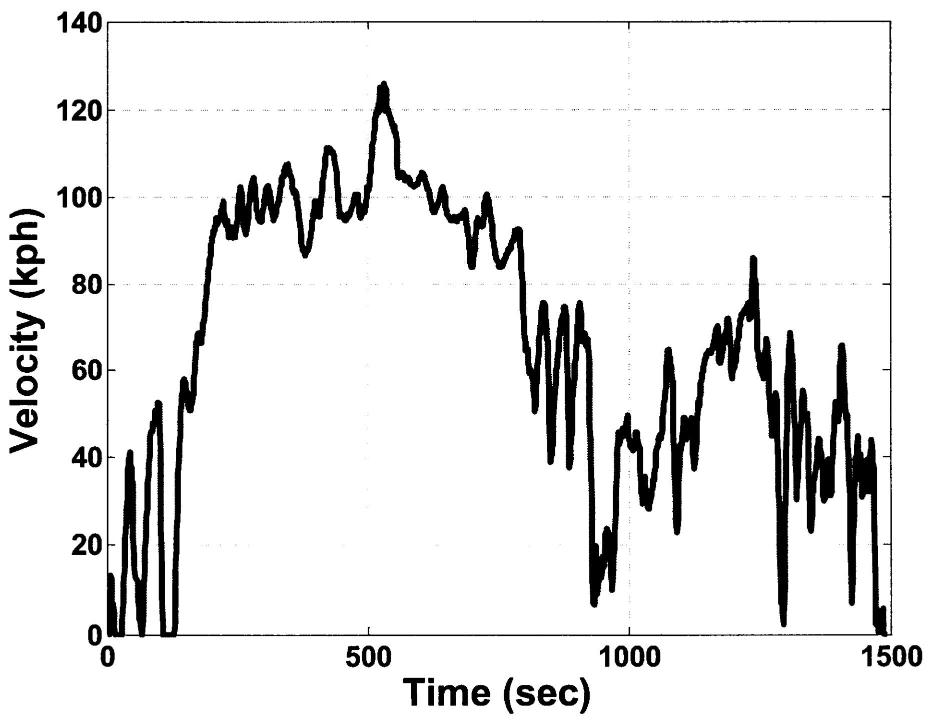

Figure 113: The INRETS road2 drive cycle

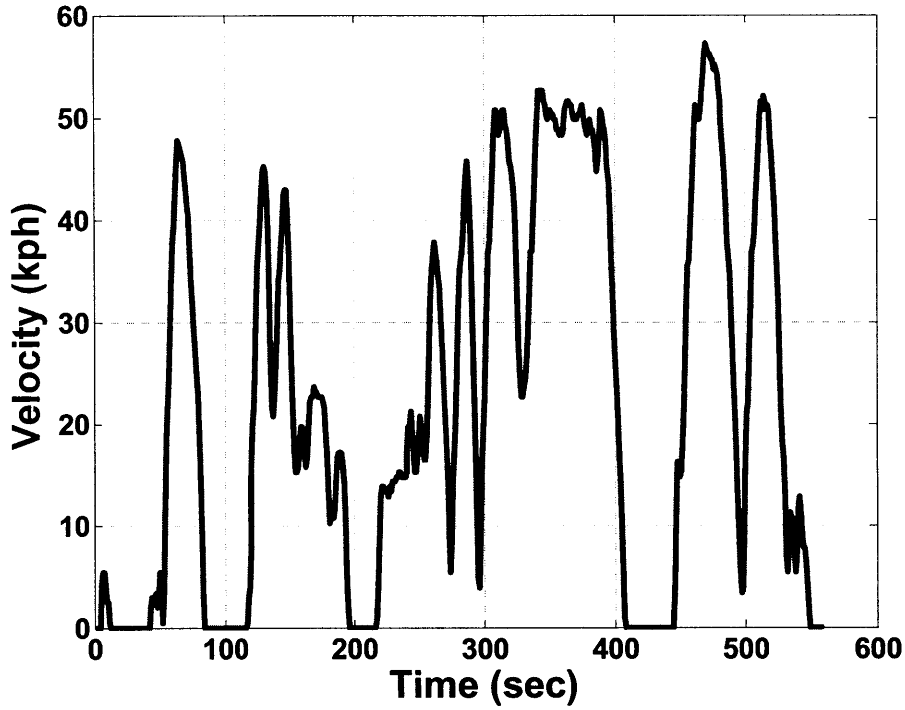

Figure 114: The INRETS urban drive cycle

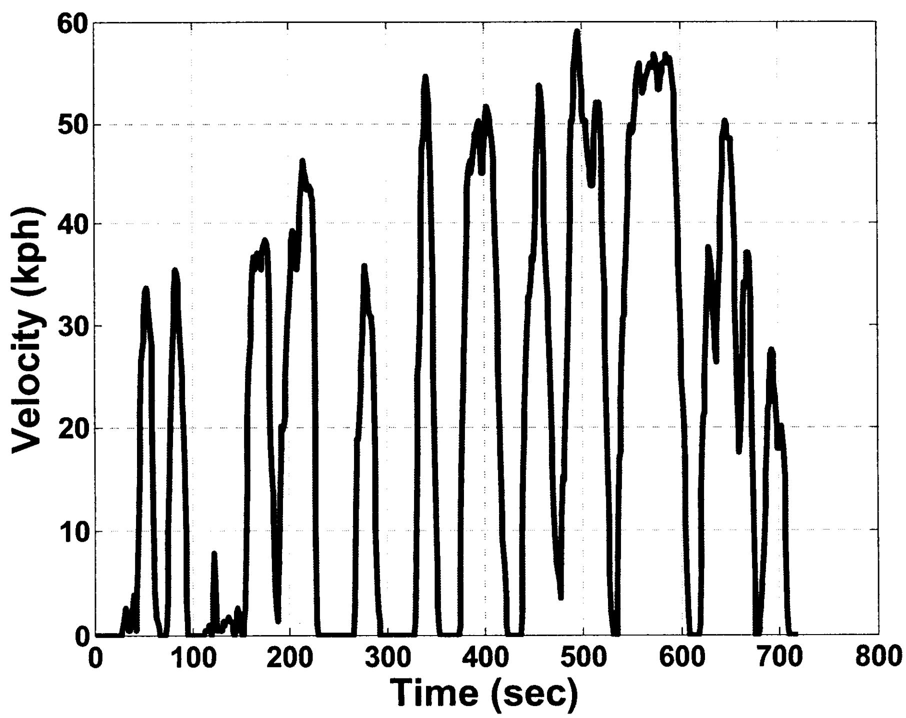

Figure 115: The INRETS urban1 drive cycle

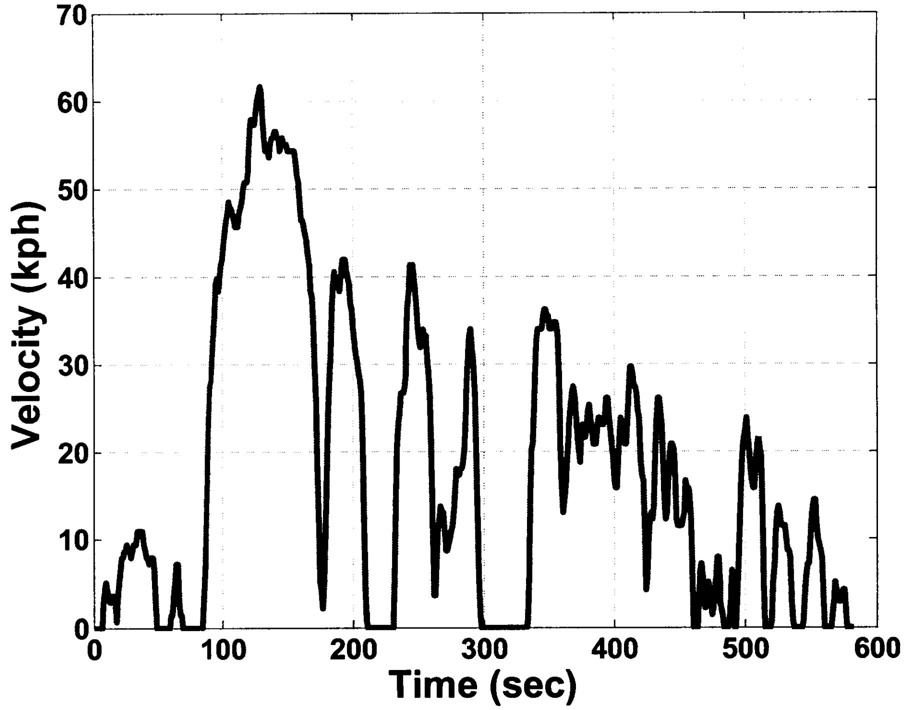

Figure 116: The INRETS urban3 drive cycle

Appendix B: 100-Car Study

Table 29: Coastdown coefficients and curb masses used to calculate Aggressiveness Factors for the vehicles of the 100-Car Study

	1	2	3	4	5	6	7	8	9	10	11
Make and Model	Ford Explorer	Ford Taurus	Chevy Cavalier	Toyota Camry	Chevy Malibu	Toyota Corolla	Ford Explorer	Chevy Malibu	Ford Taurus	Toyota Camry	Ford Taurus
Curb Weight (lb)	4,000	3,500	2,600	3,000	3,000	2,400	4,000	3,000	3,000	3,200	3,500
A Coefficient (N)	181.4	128.6	110.5	129.9	120.5	121.9	181.4	120.5	128.6	129.9	128.6
B Coefficient (N·s/m)	2.42	1.93	2.21	2.60	2.00	1.83	2.42	2.00	1.93	2.60	1.93
C Coefficient ($N \cdot s^2/m^2$)	0.62	0.43	0.42	0.43	0.42	0.42	0.62	0.42	0.43	0.43	0.43