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16. Abstract
A specific Vcost model was developed for Texas conditions based on a sophisticated fuel model for light duty vehicles, several excellent sources of secondary vehicle cost data, and the ability to measure heavy truck fuel consumption through both experimental and survey work. The basic model was designed to address the relatively narrow range of pavement roughness found on the Texas highway network and is free-flow, and does not accurately measure congestion effects. The team developed a vehicle classification scheme that was suitable for TxDOT planning and revenue forecasting. These resources led to the adoption of eight categories of light-duty vehicles and two heavy truck types. The current Texas fleet composition was determined from 2007 VTR data and was made a default for model use. Each cost item associated with the representative vehicle was calculated for each year of operation up to 20 years. Six main cost categories are included in the Vcost model: depreciation, financing, insurance, other fixed costs, repair and maintenance, and fuel. These costs fall into two categories: fixed and variable costs. The Vcost model can provide operating cost estimates for each specific representative vehicles as well as fleets of vehicles. The model allows the user to change key parameters so that the cost calculation is specific to any particular situation, and can be updated as the economic or technological landscape changes. The model was designed to provide the user with a program that looked, felt, and operated in a similar fashion to most Windows programs and would be intuitive for the typical TxDOT user.

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Estimating Texas Motor Vehicle Operating Costs

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Disclaimers

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Chapter 1. Introduction

1.1 Background and Introduction

Transportation is derived from social, political, and economic needs, the latter being a key element in moving goods from producers to markets. Those providing transportation services over a specific transportation system—such as truckers in the case of TxDOT—have to take care to understand and control costs, so that they can remain efficient and provide competitive services. This is true of all modes—water, highways, rail, pipelines, and air—that are not monopolistic. Where the entity builds, maintains, and controls the use of the infrastructure (like rail road companies), care is taken by management to ensure that the consumption of the infrastructure, in this case the track, does not exceed the revenue generated by the train movements. If heavy axles are needed (such as for coal), stronger and more expensive rails are needed and must be economically justified by long term revenue rates per ton mile that exceed cost rates.

When one entity provides the infrastructure and many use it, as with highways, the picture is more complicated. Pavement engineers use forecasts of equivalent standard axle loads (ESALs) over the lifecycle of the highway section to determine sub grade, materials, and layer thickness and material. Truck volumes play an important role in this process, as do estimates of higher truck volumes and/or changes that increase truck size and weight on the grounds of productivity. And where load life and heavy loads are predicted, rigid concrete designs are used if the construction budget is unconstrained.

Ideally, the costs of providing and maintaining the infrastructure, together with the costs of users operating a wide variety of vehicle types, should be aggregated and discounted over the life of the pavement, utilizing different designs and maintenance strategies. The design with the lowest net present value (NPV) is the preferred strategy on the grounds of economic efficiency. The challenge in applying this economic model comes with determining how vehicle user costs (Vcost)[1] vary with highway design characteristics. Researchers have addressed this issue in the U.S for over 90 years, beginning with the challenge of improving rural unpaved (and sometimes non-engineered) highways so that the growing number of autos and motor trucks could move more effectively. Fuel experiments in Iowa and the calculation of time savings were used to estimate the benefits (lower costs, higher productivity) in rural areas both to farmers and those providing public services, most notably the US Postal Service.

The next chapter details Vcost research highlights since the Second World War, particularly the 1970s when several global initiatives produced models relating Vcost to highway design characteristics. In Texas, the last significant completed Vcost study—NCHRP 01-45—began at the close of the decade and produced results that still form part of several highway planning models, ranging from work zone queuing (QUEWZ) to cost-benefit analysis (MicroBencost). The Texas study derived fuel estimates from a small representative vehicle fleet and related these, together with estimates of other operating costs, to pavement conditions, especially the condition most obvious to users: roughness. But how do you transform experimental results derived over 25 years ago to match current conditions? Typically, the technique relies on adjusting the price and cost results by inflating the values using an

[1] Traditionally these were termed VOCs but the current use of this acronym to represent volatile organic compounds in emission studies encouraged the authors to adopt a different term.

appropriate index. This is not without risk because a significant bias (related, for example, to changes in engine design) lessens the utility for policy makers and highway designers and planners alike.

Many decisions that operators face on a regular basis involve trade-offs between capital and labor, choices in vehicle technology, adoption of ITS, and more recently legal requirements and capital that have all changed substantially since the early 1990s when the Texas tests were undertaken. Stated succinctly, they no longer transfer adequately and need to be updated; this was the reason for funding the study. In addition, Vcost impacts have expanded beyond the provision, maintenance, and enhancement of the highway system. They now impact the funding of both public and private (tolled) highways that are needed to meet the mobility needs of the state over the next two decades. The funding of public highways through fuel taxes (more accurately fees) is now severely constrained by (a) reductions in vehicle miles of travel (VMT) as a result of the current recession and changes in freight VMT from new logistics practices, (b) new engine and hybrid technologies focused on reducing fuel consumption, and (c) improved truck aerodynamics and lower rolling resistance tires, all of which combine in various ways to lower fuel consumption and the resultant taxes/fees to state and federal highway agencies.

This revenue decrease is compounded by the fact that fuel taxes/fees were last updated in 1993, yet must remedy concerns and needs by projects calculated in 2009 prices. Finally, truck use of tolled highways and the potential provision of truck-only toll lanes are stymied by the current difficulty in calculating both the costs and benefits facing truckers contemplating toll road use. Clearly the per-mile benefits must exceed the per-mile toll fees if trucks are to regularly use a tolled highway. Truckers are rational and it may be that toll authorities are not using Vcost information to set attractive fees. The evidence suggests that many toll highways in Texas are designed to attract auto use, leaving trucks on the public highways and contributing to higher congestion levels.

1.2 Study Design

Study 0-5974 was a two-year study designed to produce an array of results that would allow TxDOT planners to better estimate the economic consequences of various engineering strategies and permit the Department to accurately estimate future revenues—an important benefit given TxDOT's constrained budget. Fuel was to receive significant attention by developing or calibrating the latest mechanistic models, corroborated by trucker surveys and interviews. This was a major step forward in developing a fuel model capable of predicting consumption over the coming decade. Earlier, it was noted that several Vcost studies were undertaken in the 1970s; among them the World Bank supported a Brazilian study that culminated in the Highway Design and Maintenance (HDM III) study. The U.S. company that contributed to the Brazilian study (the Texas Research and Development Foundation) undertook the NCHRP 01-45 study. HDM III was updated in the late 1990s by incorporating an earlier mechanistic fuel model and this model was the apparent recommended choice for the current NCHRP Vcost study that has not yet published any results. The 0-5974 study is therefore broadly consistent with the national study in direction and is already capable of determining free-speed Vcost estimates for Texas conditions.

The study outline is given in Figure 1.1 and shows the sequencing of research tasks developed at the start of the work. NCHRP results were not available at this time and so could not be used for comparative purposes. The central products were a total Vcost model that could be easily used by all TxDOT planners and two fuel consumption models, one for light duty vehicles (gasoline), of which there are over 190 million registered in Texas, and a heavy truck (diesel) model for the vehicles most critical to the Texas economy.

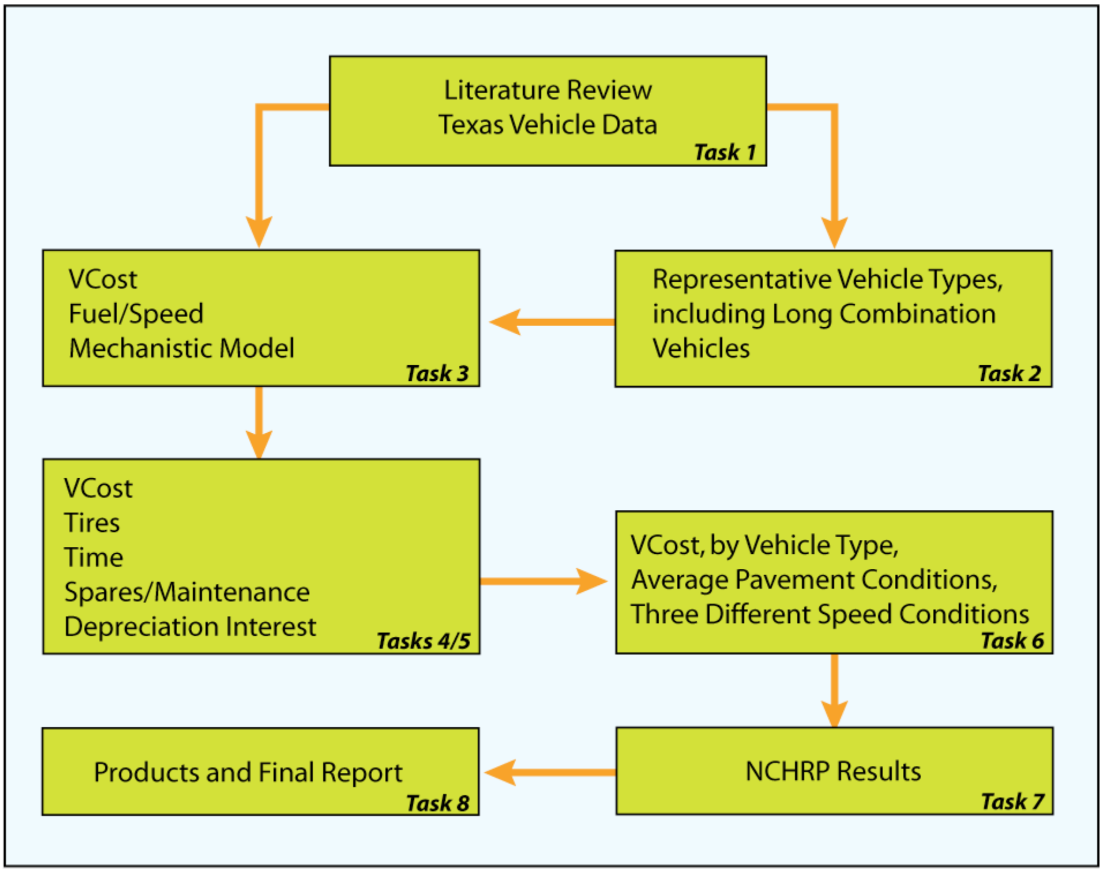

Figure 1.1: 0-5974 Study Task Outline

1.3 Report Outline

This report summarizes the work undertaken, major findings, and the products produced by the research team. Chapter 2 examines the literature on Vcost elements, particularly recent work on transferrable mechanistic models. Chapter 3 addresses a relatively new area impacting Vcost estimation, namely new federal mandates covering air quality, emission standards and idling, which, when combined with hours of service changes, have created substantial technical challenges for engine designers (particularly for diesel engine vehicles) and trucking operators. This issue will only grow with concerns about global emissions and the higher price of conventional petroleum-based fuels. Chapter 4 examines the choices of vehicles to be studied in the project based on the state-registered fleet data and weigh-in-motion (WIM) reports. The wide variety of auto and light duty vehicles in Texas requires a method that adequately addresses the large number in this set. Typically, Vcost studies chose three light duty types and this study has the potential to report over 15 different light duty vehicles. Chapter 5 describes the extensive work undertaken on the measurements of fuel consumption—an issue critical to both total Vcost estimates and TxDOT revenue estimation as noted earlier. Chapter 6 reports the total Vcost model (together with a user guide) developed in this study. Finally, Chapter 7 summarizes the work completed and identifies further study areas, notably the impact of hybrid engine and transmissions in both the light and heavy duty vehicle sectors. Eight appendices covering a variety of technical results and data supporting the main text complete the report.

Chapter 2. Literature Review

This chapter comprises a brief historical review of vehicle operating cost (Vcost) literature that the research team reviewed and utilized as the Vcost model was developed. The research team also used this literature as it developed the fuel estimates and models discussed in Chapter 4.

2.1 Brief History of Vehicle Operating Cost Research

Table 2.1 identifies the major VCost highway studies that have been conducted since 1950. Previously, various research studies into operating costs had been conducted since the late 1920s by Agg, Moyer, and Winfrey in an attempt to relate the cost of improving various highways to the benefits that accrue to the uses of these roads. In the early 1950s, an appraisal manual incorporating road user costs was provided by the American Association of State Highway Officials (AASHO, 1952; revised 1960). Although the manual initially gave data only for a passenger car and a truck, it established the principle of conducting economic evaluations of highway improvements for planning purposes. In the 1960s, Winfrey, who is the father of U.S. VCost data, synthesized available experimental survey operating cost data to produce two publications that profoundly influenced highway planning in the U.S. for the next 15 years (Winfrey R., 1963 and 1969).

Table 2.1: Major Vcost Studies Since 1950

Vcost Study	Comments
AASHO, 1952 and1960	“Red Book” auto and truck operating cost data
Winfrey, 1963 and 1969	Established Vcost data in 1960s for economic evaluation
deWeille, 1966	Compendium—used by World Bank
Claffey, 1971	Specialized in experimental fuel/speed curves
Zaniewski, et. al, 1982	NCHRP 01-45; Vcost, fuel consumption, pavement type and condition
Chesher and Harrison, 1988	Vcosts from World Bank studies
World Bank HDM 3, 1988	Vcost relationships from World Bank studies, used for next decade
HDM 4, 1998	Multi-institutional update to HDM 3
NCHRP 01-45, 2006	Vcost on Pavement Condition for U.S

Winfrey’s comprehensive review of U.S. vehicle operating costs literature revealed gaps and deficiencies that were filled by data from his own records, from discussions with staff in the motor industry and by judicious use of theoretical reasoning. Winfrey's work was synthesized by de Weille, who in 1966 developed a set of tables used by World Bank economists in their evaluations of highway investment programs. However, it became clear that a greater degree of accuracy was needed when applied to those countries undergoing rapid development. Accordingly, in 1969 the World Bank initiated a program of research to develop models relevant to the tradeoff between initial construction costs, future maintenance expenditures, and road user costs for alternative highway design and maintenance strategies. The framework for this work was developed by the Massachusetts Institute of Technology, the World Bank, and the UK Transport and Road Research Laboratory and adopted by four subsequent studies (Moavenzadeh, F. et al., 1971). The studies were conducted in India (CRRI, 1982), Africa (Hide, et al., 1975), the Caribbean (Hide, 1982), and Brazil (GEIPOT, 1981). This work was summarized in a World Bank publication (Chesher and Harrison, 1984) and formed the basis of the Highway Design and Maintenance Model: Version 3 (HDM), which was subsequently used in over 120 countries over the next decade (Watanatada et al., 1987).

In the United States, an updated version of the Federal Highway Administration (FHWA) Vehicle Operating Costs and Pavement Type Manual was published in 1981, which revised earlier work derived from Winfrey and Claffey user cost documentation. Lookup tables reported operating costs for a range of vehicle types at constant speeds and speed cycles. The Texas Research and Development Foundation (TRDF), a consultancy based in Austin, also contributed to the work. They conducted a series of fuel experiments on paved roads using a test fleet of four cars, a pick up, and three trucks (Zaniewski, et al., 1988). They also modeled tire wear using mechanistic procedures developed by U.S. Forest Service rather than from operator records (Della Moretta and Sullivan, 1976).

The next large study of any significance was undertaken in the Far East with funding provided by the U.K., Sweden, Asian Development Bank, and the International Federation of Concrete Manufacturers. Their task was to modify HDM: Version 3 to reflect newer technologies, a wider variety of vehicle users (including animal-powered vehicles), and some level of congestion. This model has proved more challenging to calibrate, particularly with respect to congestion, but remains the World Bank's main evaluation tool used in its highway investment programs (PIARC, 1998; HDMGlobal 2005). Finally, in the United States, a large NCHRP study 01-45 entitled *"Models for Estimating the Effects of Pavement Condition on Vehicle Operating Costs"* was started in 2007 and involved several phases that were expected to run roughly parallel to the proposed time frame of this TxDOT research project. The NCHRP study relates vehicle operating costs in different regions of the United States to pavement conditions. It was expected that the study could be useful influencing and/or improving the products of TxDOT study 0-5974, but unfortunately no results of this study have been released for the CTR team to evaluate.

2.2 Current Research and Literature on Vehicle Operating Costs

VCost literature was reviewed throughout the study duration of the study and sources included academic, industry, and commercial estimates of VCosts. Various academic institutions, private-sector parties, and trade organizations produce VCost studies that vary widely in scope and methodology. Studies range from focusing solely on personal light duty automobiles to primarily on commercial trucking, while some encompass both categories. While some VCost estimates capture the total operational cost, others focus exclusively on the variable costs of operation. While some studies are contracted out to governments for public policy planning reasons, others are produced by trade organizations to inform business operations; still others, such as the American Automobile Association guide, exist to educate the consumer. These disparate motivations and focuses result in a wide and diverse body of VCost estimates. The most modern and pertinent publications on VCosts are outlined below.

2.2.1 Government & Academic Studies

In 2003, a Minnesota Department of Transportation (MnDOT) commissioned report was released on the per-mile cost of truck and automobile operation (Barnes and Langworth, 2003). This cost estimate focused on variable rather than fixed costs as the MnDOT sought to use it as a tool to compare costs in traffic planning—for example, a congested corridor versus a longer but less congested route. The study investigated both the costs of personal vehicles and that of commercial trucks.

The cost estimate consisted of five main factors: fuel, routine maintenance, tires, unanticipated repairs, and depreciation. Because the Vcost estimate seeks only mileage-based costs, the depreciation cost was based solely on the depreciation due to mileage and thus is lower than the vehicle's overall depreciation, which is also based on the age of the car. The MnDOT Vcost analysis differs from many in that it takes into account the life-cycle costs of cars, whereas many Vcost analyses (notably that of AAA) only take into account the first 4-5 years of vehicle life. This study also took into account highway, urban, and congested-urban traffic conditions, as well as pavement roughness, via the use of multiplicative adjustment factors. The MnDOT report also provided Vcost estimation flexibility, as it provided a spreadsheet calculation tool that can be adapted to future conditions, rather than a static estimate that is prone to obsolescence.

This study used Intellichoice.com's Complete Car Care Guide for maintenance, repair, and fuel economy data for personal automobiles. Fuel economy is dependent on the ratio of city to highway driving, and can be further adjusted by the level of congestion. Because Intellichoice.com only estimates the repair cost for the first 5 years of a car's life, the study assumes that 50% of the total 5-year cost occurs in the fifth year. It then assumes the car has this same 50% repair cost every subsequent year. The study attempted to capture the higher utilization by assuming that 33% of mileage was driven by cars less than five year old[2]. Repair costs were adjusted with a pavement roughness multiplier, a city/highway driving multiplier, and a 3% annual inflation rate. Mileage-based depreciation was found from the N.A.D.A. Official Use Car Guide. A different rate was used for cars less than or greater than 5 years old. This was also adjusted by utilization by the same method as repair. The personal fleet was approximated using data from Ward's Automotive Yearbook; national sales by model and state sales by make were combined to get the distribution.

For trucks, only one truck type was modeled—that of a 5-axle semi-truck. Prices of truck maintenance were found from literature and adjusted for inflation. The adjustment for traffic congestion stop-start conditions was assumed to be the same as for a passenger car. Overall, the Vcost estimation for trucks involved many approximations and was not as detailed and in-depth an analysis as that for personal vehicles.

Levingston et al. (2005) addressed the operating costs per kilometer of commercial trucking firms in Minnesota. A survey of trucking firms was conducted and served as the basis for the cost estimate. The study focused on the aggregate cost of truck operation, rather than breaking it into cost categories such as fuel, repair, wages, etc. The cost estimate in this study

[2] They found in literature that 25% of cars and 31% of trucks/pickups were less than 5 years old.

was not designed to scale with changes in input prices; its scope was only to capture costs at the time of study. Instead, the model was designed to be responsive to firm-specific parameters such as firm size or other operational characteristics. A Cobbs-Douglas model was used to find elasticity of cost with respect to certain utilization parameters. The model showed constant returns to scale—an increase in km/load or truckload resulted in an equivalent percent increase in total cost. The survey resulted in an average cost per kilometer in Minnesota of 0.69$/km. The model resulted in an average cost of $0.64/km.

Another study (Logistics Solution Builders, 2005) evaluated the costs of trucking in each Canadian province, five U.S. regions, and along interprovincial and Canada-U.S. trade corridors. The operating costs evaluated involved typical factors such as fuel, maintenance, and licensing, as well as less commonly evaluated components such as driver wages, equipment purchase, and administrative expenses. In this, the Canadian report addresses the overall cost of doing business in the trucking industry rather than just the costs necessary to operate the vehicle. Trucks of several different axle configurations were considered in the study.

The methodology of the study involved developing a computer model to develop component and total cost estimates for vehicles, based on average cost estimates. These input cost values were determined via five basic sources of information: quotes from suppliers of products such as tires or fuel; consultation of transportation experts; union agreements on pay, working conditions, benefits, etc; consultation of regulatory agencies pertaining licensing fees, taxation, etc; and a review of published literature and other data sources.

The study provided regional costs of operation for various freight truck types. In addition, it also compared the relative costs of freight trucking versus double stack rail container shipping for several intercity corridors.

Berwick (1997) differentiates between local and intercity trucking, which are widely divergent in their operations and the corresponding costs. He focuses on intercity truckload (TL) (as opposed to less-than-truckload, LTT) and of those, specifically on owner-operators. The study was supported primarily by literature but also by industry survey. These costs were developed using a spreadsheet model. Driver wages, management, and overhead are included in the cost. The fuel cost was calculated based on a $1.25 price per gallon of diesel. Repair and fuel costs were modeled as sensitive to gross vehicle weight (GVW).

The model is responsive to user input for a variety of parameters to more closely match the operation of any particular firm. The model outputs in terms of cost per mile, per ton, per ton mile, per month, or per year. A sensitivity analysis was performed to educate the user on the responsiveness of overall cost to a 10% change of each parameter.

2.2.2 Industry & Consumer Group Reports & Guides

The Owner Operator Independent Drivers Association (OOIDA) published a survey focusing on the operational costs of its owner-operator members. OOIDA collected costs related to all facets of business, including depreciation, investments, utilization, liability insurance, permits, and all variable expenses such as fuel costs, driver meals, and repair. The average operational cost per mile was $0.84/mile, and gross income $1.26/mile.

The American Automobile Association (AAA) has researched personal (non-commercial) vehicle operating costs (Vcosts) since 1950, which it publishes annually in the report *Your Driving Costs*. This report estimates the overall cost for an average personal vehicle over a five-year period, where the vehicle is driven 15,000 miles per year, by monitoring the costs corresponding to the following categories: fuel; maintenance; tires; insurance; license, registration, and taxes, depreciation, and finance. These cost categories were collected into two broader categories: a per mile operating cost (fuel, maintenance, tires) and a per year ownership cost (insurance; license, registration, and tax; depreciation, finance.) Five vehicle categories were developed: small, medium, and large sedan; 4WD sports utility vehicle (SUV), and minivan. The 2008 Driving Costs revealed an average cost of 54.1 cents/mile for owning and operating a sedan, of which 17 cents/mile could be attributed to operating costs. The total and operating costs of a 4WD SUV were 69.7 cents/mile and 23.5 cents/mile, respectively, while those for a minivan were 57.6 cents/mile and 19.4 cents/mile, respectively.

It should be noted that a majority component of the operational cost, fuel cost per mile, was estimated based on a gasoline cost of $2.941/gallon. Because fuel prices have since risen by 15% (using the AAA fuel price index) and are expected to continue to increase, this makes the operational cost estimate conservative at best.

Also of note was the inclusion of financing as a factor of the overall ownership cost of a personal vehicle. This cost value is based on a 5-year loan at 6% interest, with a 10% down payment. In many Vcost estimates, vehicle financing is not a cost parameter. Therefore, when comparing AAA Vcost estimate to other Vcost estimates, it would be necessary to omit the financing term. Furthermore, the AAA estimate may be valid for individual use, but will be conservative when applied to business vehicles, as commercial use entails additional costs and typically higher insurance rates.

It is also of note that the methods by which the AAA Vcost estimate was generated are proprietary, so it was unclear how some of the terms were calculated. The annual AAA Vcost report is widely used for various applications, from government transportation reports to a basis for setting private industry compensation for vehicular travel compensation.

Intellichoice.com provides an estimated cost of ownership for new automobiles, with the intent of educating the consumer prior to a vehicle purchase. Intellichoice.com calculates the cost for the first 5 years of vehicle ownership. The cost categories include depreciation, financing, insurance, state fees, fuel, maintenance, repair, gas guzzler tax, and hybrid tax credit.

Depreciation is determined based on private-party trade-in value, assuming the vehicle is in good condition with 70,000 miles. Financing was based on a 20% down payment and a 60-month loan at an interest rate of 6.6%. The insurance cost was a comparative estimate, based on a person of less than 65 years of age, with no chargeable accidents and over 6 years of driving experience. The state fees cost is a weighted average of the new car fees for all states, including sales tax, registration fee, and title fee. The fuel cost was calculated based on a price of $2.87/gallon, a 60% highway/40% city driving pattern, and government fuel economy. Maintenance costs were based on manufacturer’s selected intervals and standard pricing. Repair cost was based on the price of an extended service contract that covers repairs at 0% deductable for at least 5 years, 70,000 miles.

Intellichoice provides a good baseline for comparing costs of different vehicles, but because it only looks at the first 5 years of ownership, it overestimates the actual operating cost of the vehicles. The average age of a sedan is around 9 years. Also, a utilization of 14,000 miles/year is high for the typical driver, who, according to the 2000 Census travel survey, drives closer to 12,000 miles/year.

Consumer Reports provides cost-of-ownership estimates for all new cars listed in its database, with the purpose of informing consumers on personal vehicle purchases. The costs are estimated for the first 8 years of ownership; like most consumer-based Vcost estimates, they do not take in to account the full lifecycle costs of a particular car. Costs are broken down into depreciation, interest, sales tax, insurance, fuel, and maintenance/repair.

Repair data was accumulated through their Annual Car Reliability Survey. Fuel cost was estimated from the EPA fuel economy, national average fuel price, and an annual mileage of 12,000 miles. Insurance estimates were based of Insurance Institute for Highway Safety (IIHS) data. Interest cost was premised on all cars being financed at 15% down, for a 60-month term, with interest according to the national average from bankrate.com. The depreciation cost was based off current MSRP and past resale history of the vehicle line.

Cumulative owner costs were displayed for the 1st, 3rd, 5th, and 8th year of vehicle ownership. Costs per mile were based on a utilization of 12,000 miles/year.

Consumer Reports provides a better operating cost estimate than Intellichoice, in that it looks at the first 8 years of ownership instead of just the first 5. Furthermore, their maintenance and repair estimates are grounded in empirical survey data, rather than estimates based on warranty plans. The range of vehicle ages in the Vcost estimate, however, still is not representative of the older vehicle fleet in operation and thus considerably overestimates costs.

2.2.3 Studies from Other Countries

The NRMA, an Australian organization based out of New South Wales (NSW), produces estimates of operating costs of a variety of automobile models. The costs are calculated for the first 5 years of operation of a car, assuming it drives 15,000 km/year. The costs are output in terms of average weekly fuel bill, average weekly running costs, average cost per km, and total average dollars per week. The estimate takes into account capital costs (depreciation and opportunity cost), standing costs (registration, CTP insurance, Comprehensive Insurance, and NRMA Basic Care cover), and running costs (fuel, maintenance, and tires). The vehicle is assumed to be bought outright so there is no cost due to financing.

Depreciation and opportunity interest were calculated based on dealer price plus sale fees and the residual fifth year value on the car. The opportunity cost is the depreciation times the Reserve Bank interest rate over the 5 years of ownership. Insurance calculations were based on a driver age 29 to 55 in a medium-risk suburb of Sydney. For fuel cost, the fuel economy was multiplied with a factor and then by the average price of fuel.

The Royal Automobile Club of Victoria (RACV) in Australia also provided Vcost estimates. Like the NRMA study, it investigates the ownership cost of the first 5 years of a new car, assuming a yearly utilization of 15,000 km. Its standing costs include depreciation, insurance, and financing costs, as well as purchase fees such as dealer delivery fees and state fees such as stamp duty and registration. The running costs consisted of fuel costs, tire costs, and service and repair costs.

Depreciation was the difference between the purchase price and the fifth-year value of the car. The financing cost was based on a 100% loan, with annual interest of 11.8% and a five-year term. Insurance costs were based on RACV insurance for a personal-use car with no owner driver below 30 years of age, garaged in Donvale. Fuel consumption was based off the ADR/81/01 Combined test figure from the Green Vehicle Guide. Fuel price was taken as the Melbourne metropolitan average over the last 6 months. Service and repair costs were calculated using manufacturer-recommended service schedule for service and commonly failing parts for unexpected repairs (brake pads, batteries). The average labor rate in Victoria was used.

The categories of cars analyzed included light, small, medium, and large cars; compact, medium, and large SUVs; commercial 4x2s, and commercial 4x4s. Costs were estimated for between three and twelve models per category. The models were chosen based on popularity (NRMA, 2007).

2.3 Literature Review Sources for Fuel Estimation

The research team also reviewed literature sources for the fuel estimation modeling that the project undertook, including the coast-down tests that were conducted in the second year of the research project. This task contributed fundamentally to the specific models developed by the team for fuel simulation. The literature review provided data regarding light duty and heavy duty fuel usage as well as literature regarding the development and implementation of coast-down tests.

In order to predict the fuel economy of vehicles on Texas' roadways, the "road load" force as a function of vehicle speed was required. This is the combination of aerodynamic drag and rolling resistance if the vehicle is driving on a level road with no wind. The United States Environmental Protection Agency (EPA) provides all of the information regarding fuel economy for light-duty cars and light-duty trucks on their web site. The Annual Certification Test Results Report (often referred to as Federal Register Test Results Report) includes light-duty vehicle and heavy-duty engine reports for model years 1979 through 1994 and light-duty-only data for later model years (EPA Cars and Light Trucks Annual Certification Website page, 2009). The team also reviewed the lookup table prepared by Sierra Research to understand columns of the Annual Certification Data taken from EPA's website (Sierra Research, 2000).

However, for heavy-duty trucks, the EPA web site is not useful because there are no fuel economy standards for heavy-duty vehicles and EPA does not conduct tests to ascertain their fuel economy. Therefore, the research team had to model the entire vehicle using commercially available software. In turn, the model requires the user to input the "road load" force as a function of vehicle speed. To obtain this, the research team conducted coastdown tests on a variety of heavy-duty vehicles with various payloads and a variety of tires. The research team also reviewed the literature regarding the SAE test procedure for coastdown testing procedures and details regarding heavy-duty coastdown tests operations.

Regner et al. (2002) found that in order to improve the accuracy of vehicle simulation under transient cycle conditions to predict performance and fuel consumption, consideration of the complete system engine/drive train/vehicle was necessary. The coupling of otherwise independent simulation programs is therefore necessary for the vehicle and engine. The description of thermally transient processes enables the calculation of the energy balance of the engine, which in turn enables the simulation of warming up operation. Through consideration of the engine warming up process, the quality of the prediction of fuel consumption and emissions is improved. This paper found that the combination of the AVL simulation programs CRUISE and BOOST to determine the engine energy balance has proven to be successful for the analysis of transient drive cycles.

McClair and Truemner (2005) found that the cost of fuel for commercial trucks was second only to labor in the total vehicle operating costs. Therefore, technologies that reduce fuel consumption can have a significant impact on the bottom line for both trucking fleets and owner/operators. Quantifying the fuel savings associated with different technologies, however, is complicated by many factors, and short-term testing often cannot adequately quantify small changes in fuel consumption that, over time, can add up to substantial cost savings on a vehicle. For example, fuel economy gains of less than 1% may not be reliably measurable using fuel economy tests, and variable environmental and use factors can cast some doubt on the appropriateness of short-term testing. Nonetheless, with today's fuel prices, each percent improvement in fuel economy for heavy-duty trucks results in annual savings of about $335 per vehicle in fuel costs, based on 100,000 miles (160,000 km) annual vehicle mileage, 6.5 mpg (36.2 L/100 km) fuel economy, and a fuel price of $2.20/gallon. It is therefore quite worthwhile to identify technologies that can provide even modest fuel savings and to quantify the gains. As an alternative to conducting fuel economy tests, fuel savings can be quantified through detailed simulation of a vehicle's performance using a physics-based model that incorporates performance maps of the drivetrain components and all other elements of the vehicle responsible for energy losses. This paper describes the development of a model for heavy-duty trucks using AVL-CRUISE software. This model can be used to predict fuel consumption when a vehicle is operated following any specified driving cycle, and the fuel savings potential of specific technologies can be evaluated when the energy loss characteristics of the technology are available. Results of testing are presented that were used to validate the model results. Instantaneous fuel flow measurements during various driving cycles show excellent agreement with the model predictions. The effect of tire rolling resistance on vehicle fuel consumption was investigated using the model developed. Based on these results, fuel savings of 1.40 to 1.62 L/100 km can be expected per kg/T reduction in the average rolling resistance coefficient for this vehicle, depending on the cycle evaluated. This equates to fuel savings of 600 to 690 gallons of diesel for each 100,000 miles driven, times the reduction in the coefficient of rolling resistance expressed in kg/ton.

Korst et al. (2007) found that coastdown testing with full-scale vehicles on level and inclined roads offers an inexpensive approach to road load determination and, in particular, aerodynamic force evaluation, provided that drag component extractions can be accurately achieved under random instrumental disturbances and biased environmental conditions. They found that wind tunnel testing of large vehicles, especially truck/trailers, to establish their aerodynamic drag is costly and also may produce questionable results when the effects of the moving road, blockage, wake/diffuser interaction, and rotating tires are not properly simulated. On-the-road testing, however, is now conveniently and speedily carried out using GPS-based data acquisition and file storage on laptops, allowing instantaneous on-board data processing. Specifically, this can be done by using a spreadsheet that allows parameter identification by fitting routines applied to a "user defined function" (the latter being obtained from the solution of the equation of motion for the vehicle, including properly defined biased and randomly disturbed environmental conditions). Fitting routines, such as given by Levenberg-Marquardt and others, are part of some spreadsheets. Thus, information on tire drag and aerodynamic drag contributions can be promptly evaluated at the end of each coastdown run. Special concern arises from the sensitivity of aerodynamic drag determination under even light prevailing winds. The paper showed how to account for such disturbances by introducing the concept of "effective" wind correction by conducting coastdown runs in opposing directions. Additional difficulties arise due to the lack of separability of the drag parameters (speed dependency of tire drag), in which case one has to use information provided by tire manufacturers. The efficiency of different data processing methods is tested by the recovery of drag components from a generating program, which simulates coastdown subjected to bias and randomly disturbed conditions. Examples of actual coastdown runs with 18 wheelers and their road load evaluations are given to demonstrate the capability of the approach. Because heavy trucks and especially 18-wheeler rigs come in a great variety of configurations, selection of a reference (frontal) area for extracting drag coefficients may produce misleading results; as one observes that all important criteria for truck operation depend on the product A times C_D, it is conventional to define this product as the "Drag Area," as the most appropriate criterion for aerodynamic performance.

White and Korst (not dated) found that the problem of aerodynamic and rolling resistance characteristics of cars and trucks is of considerable importance to vehicle engineers as the two major contributions to external vehicle motion resistance. Many testing methods have been developed including wind tunnel testing of scale models, testing of full-size production cars, and coastdown testing. This research discussed and analyzed the advantages and disadvantages of each method.

Yasin (not dated) found that coastdown testing is an acceptable technique for establishing the dynamometer load that simulates the vehicle road load during EPA dynamometer fuel economy and emission testing. This paper discusses the theoretical basis of a successful approach to coastdown testing. Corrections for the effects of ambient conditions on road test results are defined, and a data-efficient method of matching the dynamometer to road load is discussed in this paper.

SAE Recommended Practice J1263 (SAE, 1966) and J2263 provide uniform testing procedures for measuring the road load force on a vehicle as a function of vehicle velocity and for simulation of that road load force on a chassis dynamometer.

2.4 Survey Work

The research team also undertook survey work during the research study to gather field data regarding operating costs from the heavy-duty vehicle industry. Interviews were conducted with HEB (a Texas grocery store chain), Wal-Mart, FedEx, Greatwide Transport, and Landstar. The research team also talked to a synthetic fuel supplier (Southwest Synthetics). The team attended the Great American Trucking Show in Dallas during August 2008 and spoke to multiple manufacturers, the Retread Tire Association, and other heavy-duty affiliated industries and suppliers.

The research team also attended the Texas Motor Transport Association's annual Fleet Maintenance Council meetings in 2007 and 2008 to gather information and meet with industry representatives. This allowed the team to also review new technologies and vehicles that were being developed and placed into the market place as a consequence of emissions legislation that was developed and introduced at the federal level

2.4.1 Tire Cost Research

Tires constitute a vanishingly small percent cost for light-duty passenger vehicles, and thus are not disaggregated from overall maintenance costs. Therefore, our research on tires focused predominantly on commercial trucks.

Historically, tires have constituted an appreciable fraction of truck operating costs. Recent advances in tire technology, such as increased tread life, recaps, and super-wide tires, have reduced the cost of tires to a small percentage of the overall operating cost; current estimates put the cost between two and three cents per mile.

The significance of tires reaches beyond their operational cost. Low rolling resistance tires can improve fuel economy by several percent. This effect on fuel economy is much more significant than the overall cost of the tires themselves. Though low rolling resistance tires are starting to show promise in the passenger vehicle market (TRB, 2006), they are of primary interest in commercial trucking. In this field, super singles, as well as low rolling resistance conventional tires, are increasingly adopted by industry in order to lower fuel costs.

In researching tires, both a literature review and a survey of trucking professionals were conducted. A 2006 American Trucking Association (ATA) study found tire costs to be 2.66 cents/mile (ATA, 2006), while a 2008 American Trucking Research Institute (ATRI) study found is to be 3 cents/mile (ATRI, 2008). A survey by OOIDA found the median tire cost of an owner-operator to be 2.72 cents/mile (OOIDA, 2003).

Industry surveys revealed a tire cost of between 2 and 3 cents/mile, which was validated by multiple sources.

Tire Technologies

Retreading

In retreading, tires that are reaching the end of their tread life are renewed by a process that reforms new treading to the casing of the tire. In remolded tires (remanufactured tires) the sidewall of the tires are also renewed. First the casings are inspected for any defects or abnormalities that would prevent the tire from being safely retreaded. Advanced electronic forms of inspection and even X-ray technology are used to look for microscopic defects. After this, the old treads are buffed off and any necessary repairs made to the casing. New tread is then applied to the casing in a vulcanizing process. The new tread is cured and then subject to a final inspection. Retreading tires are attractive in that the process costs only 30-50% the cost of replacing with a new tire.

In our survey data, we found that retreads were widely used in fleets as a cost-saving method. Private fleets provided detailed information concerning tire cost savings and recap rotation schedule, which were are as inputs to the truck Vcost model. Generally, tires taken from the drive and steering axles are recapped and rotated to the trailer. There was a notable large fleet that did not use recaps, as the logistics of the company made it difficult to track and monitor the retreated tires.

Widebase Tires

Widebase tires[3] are wide tires, each designed to replace two of the conventional dual tires on each of the truck's axles. The advantage of using widebase tires is the lowering of the rolling resistance, which increases the fuel economy of the vehicle. A 3% reduction in rolling resistance roughly equates to a 1% fuel savings.

Although wider than a conventional dual, the use of just one tire instead of a pair greatly reduces the overall surface area of tire on the pavement. While this leads to a greater average load concentration incident on the pavement compared to conventional dual tires, operators are allowed the run widebase tires because they distribute force more evenly than standard tread tires, resulting in less force concentration areas that lead to pavement wear.

Thus the advantage of widebase tires is not primarily in the tire cost, as a result of having fewer tires, but in the fuel cost, which is much more significant. Numerous studies have shown fuel, along with driver compensation, to be one of the two dominant costs of operating a commercial truck [Bernwick, 1997, *Logistics*, 2005], whereas tire cost is a small percentage, around the order of 2%, of the overall cost.

Despite their obvious advantages, widebase tires are slow to reach widespread adoption in the industry, primarily due to logistical complications and delivery restrictions impacts tire

[3] Also known as *super singles*, *super wides*, *single wides*, and *wide singles*.

sidewall damage. A lack of market penetration throughout service shops mean that these tires may not be available in a region should the operator experience a blow out. The time spent waiting for a replacement tire to be delivered from a more distant location would have a negative economic effect that would negate the fuel cost benefit. In our industry survey, concern about nationwide availability was the most commonly cited reason for non-adoption of widebase tires. In addition, delivering to warehouses and other distribution and customer locations with sharp turn-ins and high curbs can result in sidewall damage that can instantaneously ruin a tire carcass. The widebase tires did have widespread adoption among the fleet of a Texas grocery distributer sampled but conventional tires were used for a number of distribution routes.

Low-Rolling Resistance

For those not interested in moving to wide-base tires, most tire manufacturers also now make low rolling resistance dual tires. Although using low rolling resistance duals do not manifest in the same reduction in rolling resistance as widebase tires, they provide a significant increase in fuel economy over conventional tires. Low rolling resistance tires have also been developed for the personal vehicle market, but have not yet seen widespread adoption.

2.4.2 Tire wear model

Information from literature and survey sources was used to develop a beta version of our tire wear model. This model represented a truck using conventional dual tires with retreading. The results of this model were shown to an industry representative who validated the results.

2.4.3 Other Findings

Regional variations have been shown to affect tire costs. According to one industry representative, the Houston area trucks exhibited greatly increased tire wear, resulting in a roughly 17% elevated cost of tires. This was thought to be in part because of the regional pavement composition, which contains a sharp shell substrate; and regional road construction, where sharp curves lead to increased tire abrasion.

2.5 Summary

This chapter reviewed some of most relevant literature in the Vcost area and focused on the estimation of fuel consumption, an issue of great importance for TxDOT, both in terms of cost-benefit work and revenue estimation. A major conclusion was that fuel models needed to be up-to-date and calibrated to Texas conditions. It was decided to use an existing sophisticated fuel model for light duty vehicles, and to develop a truck fuel model specifically for heavy trucks from experimental data determined from this study. Survey data from a wide range of sources would complete the full range of Vcost elements.

Chapter 1 described the various EPA programs that have "framed" the rapid change over the past decade taking diesel engines from relatively simple mechanical systems to complex computer-controlled systems. The main driver in this has been the EPA, which introduced three emission standards and was behind the move to low sulphur diesel, a move that has completely changed trucking equipment and the emissions produced by the truck sector. The next chapter covers the U.S. legislative and policy developments that necessitated a change in Vcost estimating models.

Chapter 3. Legislative and Policy Developments

3.1 Background

There have been far reaching changes made to legislation, regulations, and the air quality landscape at the federal and state levels since vehicle operating costs (Vcost) were last estimated in Texas. Legislation not only affects state and local area planning, but also the development of average fuel economy and emissions technology for on-road sources of emissions. Rule making affects operational changes, such as the implementation of idling regulations and hours of service rules.

As part of the literature review for this project the research team reviewed legislation and litigation regarding fuel economy, emissions, greenhouse gases (GHG), and alternative fuels and technologies. This provided an insight into the standards that have been set federally and within the states (specifically California) as well as reviewing litigation that has led to development of new standards regarding fuel economy, emissions, GHG, and alternative fuel development and use. The review of major litigation also encompassed the Heavy Duty Diesel Engine Settlement, between heavy duty truck manufacturers and the EPA that led to the implementation of new emissions technology to reduce truck emissions.[4] The team also reviewed other policy initiatives that have been changed over the past 25 years, especially with regard to trucking. The most important change that occurred in the past 10 years was the change to the Hours of Service Rules, which impacted truck drivers and changed the number of hours a heavy-duty truck driver could continuously drive without a break. Another major policy change has been the introduction of idling reduction policies, which restricted truck idling in many areas of the country that were facing decreasing air quality or were in non-attainment

The two decades since vehicle operating costs were last reviewed can be analyzed through two separate prisms: (i) long periods of stagnation, and (ii) epochal eras of dramatic change smattered with litigation and discord. The 2008 Light Duty Automotive Technology and Fuel Economy Trends Report produced by the EPA concluded that:

> "Since 1975, overall new light-duty fuel economy has moved through four phases:
> 1. A rapid increase from 1974 through the early 1980s,
> 2. A slower increase until reaching its peak in 1987,
> 3. A gradual decline until 2004, and
> 4. An increase beginning in 2005." (EPA, 2008).

No doubt litigation that occurred has been a driver of the changes we have seen enacted. Similarly, the recent higher energy costs that the U.S. saw in 2008 (oil at a record of high of $148 a barrel, and diesel and gasoline reaching $5 and $4.25 averages respectively in 2008) impacted U.S. driving habits and the propensity for future fuel increases may well impact emissions and fuel efficiency policy going forward. Data from the U.S. Department of Transportation (DOT) and the Federal Transit Administration (FTA) showed that Americans were driving less and utilizing transit more with this trend continuing into 2009 as gasoline prices dropped dramatically. During 2008 many transit operators saw double digit increases in ridership. The DOT announced in 2009 that Americans had driven 112 billion fewer miles year since 2007 (DOT, 2009).

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[4] This is also often referred to as the Consent Decree.

After many years of stagnation on this front, at the federal level the Obama administration is changing the landscape vis-à-vis environmental procedures, GHGs, and emissions. The American Recovery and Reinvestment Act of 2009 provided funding for energy projects to reduce emissions. The 111^{th} U.S. Congress is also currently debating bills regarding climate change legislation. These policy changes will impact fuel efficiency.

With the bankruptcies of General Motors and Chrysler, and the restructuring of the U.S. auto manufacturing industry, the dynamics of vehicle manufacture and sale will also change. In fall 2008 the U.S. Congress gave the “Big Three” U.S. automakers $25 billion to re-tool U.S. plants to produce fuel efficient and hybrid vehicles. How long this retooling will take may depend upon (i) the economic downturn that began in 2008 and (ii) the demand for fuel efficient vehicles whose elasticity has been shown to be dependent upon gasoline prices.

In mid 2009 the Obama administration ramped up the “Cash for Clunkers” program that gave cash allowance between $3,500 and $4,500 to encourage motorists with older, less fuel efficient vehicles to trade in their gas-guzzlers. This program was an unmitigated success and required Congress to inject an extra $2 billion into the program when the first billion ran out after a couple of weeks. The program officially ended on August 24, 2009, and according to the DOT over 700,000 vehicles were traded in and taken off the road (DOT, 2009a).

3.2 Fuel Economy Standards Overview

3.2.1 Automobile and Light Truck Fuel Economy—The Corporate Average Fuel Economy (CAFE) Standards

After the Arab oil embargo of 1973-74 focused attention on the variability of supply of crude oil and the fuel inefficiency of the U.S. fleet, Congress passed The Energy Policy and Conservation Act (EPCA) of 1975. Prior to this fuel economy for the U.S. fleet had declined from 14.8 mpg in Manufacture Year (MY) 1967 to 12.9 in MY 1974.

Under § 502 of this Act the Secretary of Transportation was required to promulgate rules to establish maximum feasible average fuel economy standards for automobiles (49 U.S.C § 32902(a)-(c)). The standards called for a doubling of fuel economy. The Secretary of Transportation, according to Yacobucci, has great latitude in setting Corporate Average Fuel Economy (CAFE) standards for light-duty trucks and passenger vehicles (Yacobucci, 2007). This authority has been delegated to the National Highway Traffic Safety Administration (NHTSA) to set CAFE standards for vehicle classes including light trucks. However, the authority to alter passenger car programs is set by the EPCA. There is no fuel economy standard set for heavy-duty diesel engines.

NHTSA is responsible for the administration of the program. This includes establishing and amending the standards, promulgating regulations, establishing CAFE standards, considering petitions for exemptions from low volume manufacturers, classifying vehicle lines, recording and cataloguing mid and end year reports, adjudicating back credit plans, and enforcing compliance (NHTSA, Overview). Penalty for non-compliance is $5.50 for each 0.1 mpg below the standard multiplied by the number of cars in the manufacturer’s new car fleet for that year. According to NHTSA civil penalties collected between 1983 and 2006 totaled $735,422,635.50 (NHTSA, 2007).

The EPA is responsible for calculating the average fuel economy for each manufacturer. This certification is done one of two ways.

1. The manufacturer provides its own test data; or
2. EPA obtains a vehicle and conducts a test at its facility.

According to the NHTSA, EPA will do ‘actual tests’ on approximately 30% of the existing vehicle lines and will use this test to also measure exhaust emissions. The regulations regarding the certification test procedure and the recording of data are found in Title 40 C.F.R.

The CAFE standards do differ from EPA’s fuel economy data—which probably adds to the confusion in understanding this arena. Currently there are three sets of fuel economy values.

1. The NHTSA’s CAFE values (which EPA creates for NHTSA);
2. EPA’s unadjusted dynamotor values; and
3. EPA adjusted on-road values.

NHTSA’s CAFE values, according to the NHTSA, are used to determine each manufacturer’s compliance with the average fuel economy standards and create its annual report, “The Automotive Fuel Economy Program Annual Update.” The EPA’s other two fuel economy values (city and highway) are calculated from the emissions generate during testing.

In 1975 EPCA set new standards for fuel economy for passenger vehicles for MY1978 and established new economy standards for light trucks beginning in MY1979. However, as these standards were being phased in, oil supply stabilized, and its price dramatically dropped: the policy perspective was that the U.S. was less vulnerable to disruptions in fuel supply[5]. The shift in fuel costs downward led to consumers placing less of a premium on fuel efficiency. In response to petitions from manufacturers facing penalties, NHTSA relaxed the standard for model years 1986-89. These were restored in 1990 with standards set at 27.5 mpg for passenger cars and 22.2 mpg for light trucks for MY 2007.

Separate CAFE calculations are made for three potential fleets: domestic passenger cars, imported passenger cars, and light truck fleets. The formula for determining a fleet’s CAFE standard uses an averaging method called the *harmonic mean*. It should be noted that vehicles with a gross vehicle weight that is higher than 8500 pounds were excluded from the calculation because they did not have to comply with CAFE standards (this included large pickup trucks, large sport utility vehicles, and large vans). The legislation states:

> “The number of passenger automobiles manufactured by the manufacturer in a model year; divided by the sum of the fractions obtained by dividing the number of passenger automobiles of each model manufactured by the manufacturer in that model year by the fuel economy measured for that model.”

[5] One could argue that this is still the case—to a certain degree—given the inelasticity seen in consumption over the past 36 months as prices have shifted upwards to $3 per gallon average. Whether these elasticities will continue to shift as we are seeing a $4/gallon average remains to be determined. The recent dramatic drop in gasoline prices at the tail end of 2008 have also not yet been analyzed to see if the shift we saw in VMT will continue.

For the example of light trucks, the calculation looks like this:

$$\frac{\text{Total Light Truck Production Volume}}{\dfrac{\#\ \text{Vehicle A}}{\text{Fuel Economy}} + \dfrac{\#\ \text{Vehicle B}}{\text{Fuel Economy}} + \dfrac{\#\ \text{Vehicle C}}{\text{Fuel Economy}}} = \text{Average light truck fleet fuel economy}$$

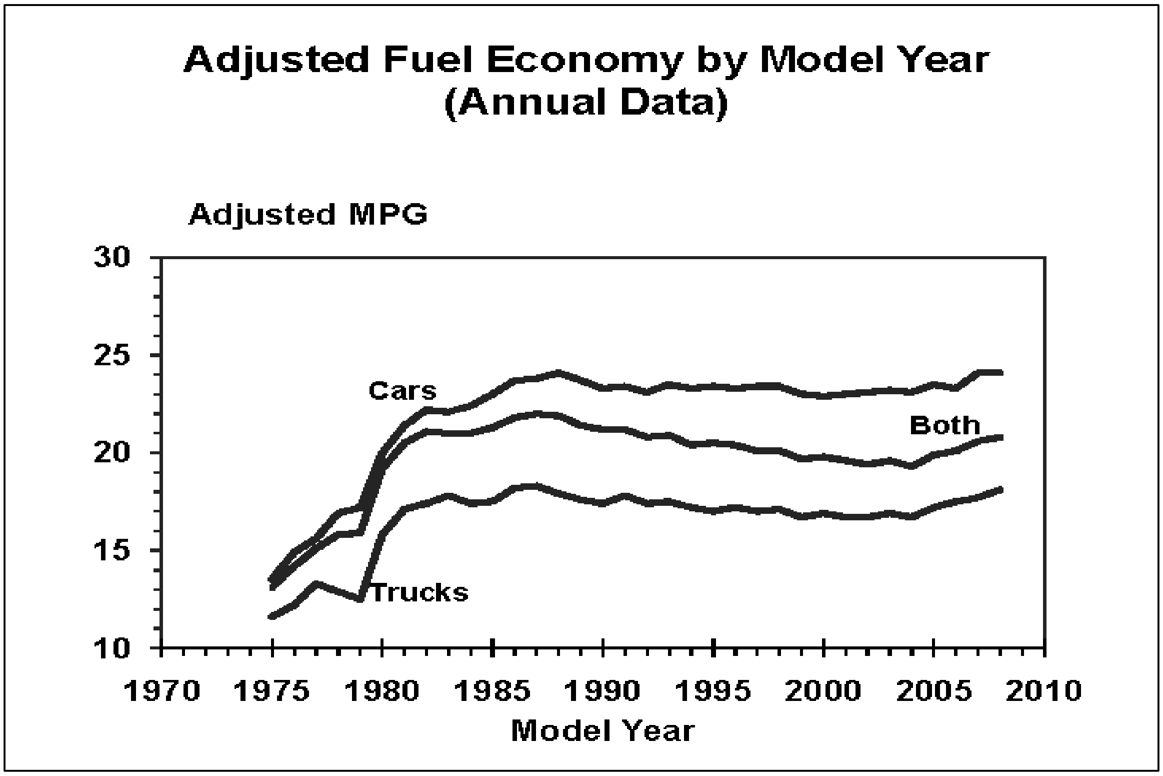
Table 3.1 shows how the CAFE standards have been amended over the years.

Table 3.1: CAFE Standards 1975–2009

Passenger Vehicles			Light Trucks		
Year Set	**By Whom**	**Miles Per Gallon**	**Year Set**	**By Whom**	**Miles Per Gallon**
1975	Congress	MY 1978—18 mpg MY 1979—19 mpg MY 1980—20 mpg MY 1985—27.5 mpg	**1975**	No target set until 1979—thereafter NHTSA was responsible	MY 1979—17.2 mpg (2 wheel drive) and 15.8 mpg (4 wheel drive). Standards for GVW <6000 lbs
1980	Left to NHTSA to determine	MY 1981—22 mpg MY 1982—24 mpg MY1983—26 mpg MY1984—27 mpg	**1979**	NHTSA	MY 1980—20.7 mpg (2WD) MY 1991 19.1 mpg (4WD) Standard set for GVW <8500 lbs *
1984	Congress	MY 1985—27.5 mpg	**1990**	NHTSA	MY 1992—20.2 mpg **
1996	Appropriation Freeze	MY 1996—27.5 mpg	**1996**	Appropriation Freeze	MY 1996—20.70 mpg
2001	Study commissioned to review CAFE standards				
2002	Study Findings Released		**2003**	NHTSA	MY 2005—21.0 mpg MY 2006—21.6 mpg MY 2007—22.2 mpg
2005	DOT Rules Released	Reformed CAFE standard released based on measuring a vehicle's footprint by multiplying its wheelbase by its track width. Six footprint categories were created with target fuel economy levels.	**2006**	NHTSA	MY 2008—22.5 mpg MY2009—23.1 mpg MY 2010—23.5 mpg MY 2011—level that maximizes benefit
New era of combined mpg for cars and light trucks					
2007	Congress	Industry wide average all passenger cars and trucks combined is not less than 35 mpg by 2020			
2008	NHTSA	Model Years 2011-2015 result in a fleet wide average of 31.6 mpg			
2009	NHTSA & EPA	Proposed rulemaking to establish light duty vehicle greenhouse gas emission standards and CAFÉ standards program			
2009	NHTSA	MY 2011- 27.3 mpg combined average for cars and light trucks MY 2016 to 35.5mpg			

** MY 1982–1991 manufacturers could comply by either combining 2WD and 4WD fleets or calculating separately.*
*** 2WD and 4WD distinction eliminated.*

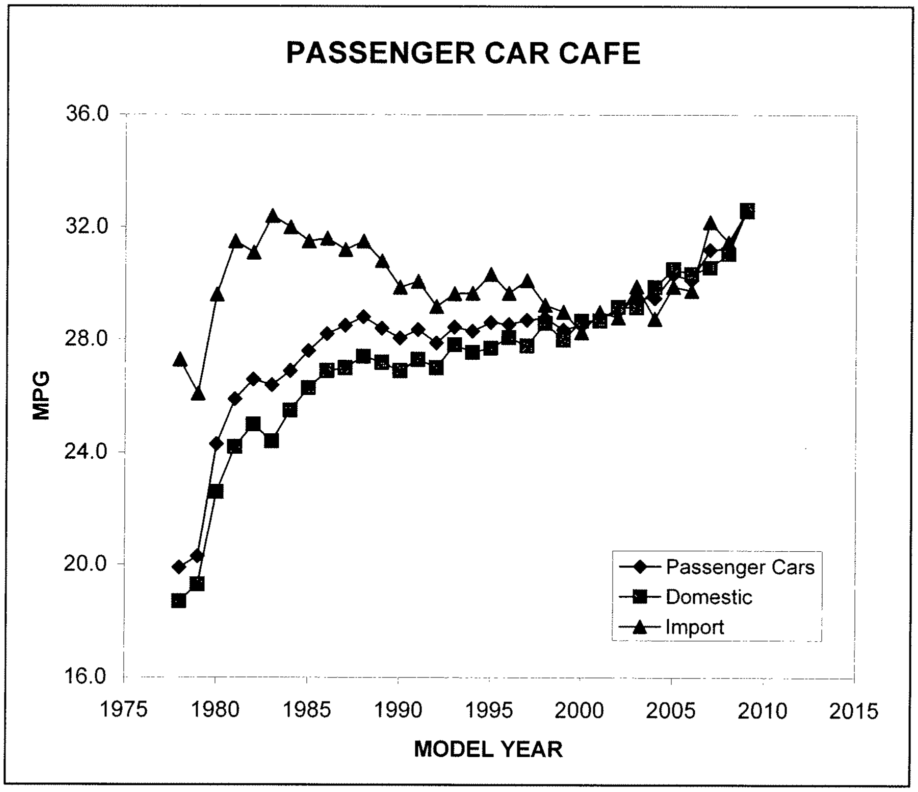
As can be seen in Figures 3.1 through 3.3, fuel economy for the passenger car fleet remained relatively flat during a period of declining gasoline prices. This suggests, according to Yacobucci, that the CAFE regulations contributed to placing "*some sort of floor under the new-car fuel economy.*" Another restriction that led to the stagnation in CAFE regulation was language that was inserted in the Fiscal Year (FY) 1996 Appropriations Bill for the DOT—by Representative Tom Delay, Texas—that prohibited the expenditure of any DOT funds on any rulemaking that would make an adjustment to CAFE standards. This prohibition continued to be included in appropriations and spending bills for the DOT for FY1997 through 2000. Figure 3.1 shows fuel economy averages for passenger cars and light trucks for model years 1975 through 2010.



Source: EPA, 2008

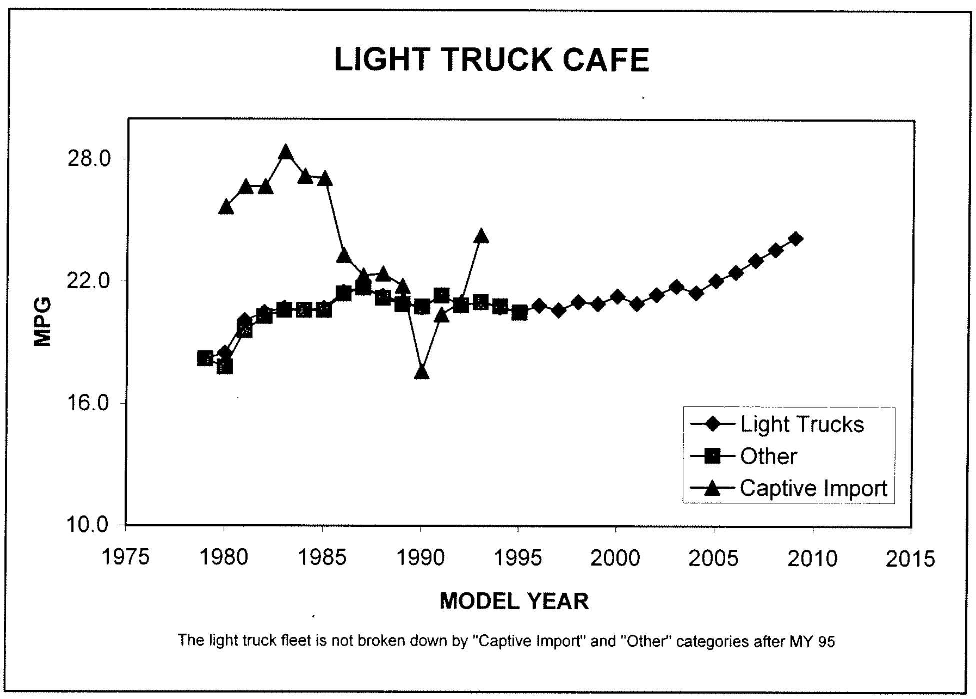
Figure 3.1: Fuel Economy Averages Cars and Light Trucks Model Years 1978-2010

Figures 3.2 and 3.3 show CAFE performance fleet data for passenger cars and light trucks between 1978 and 2010. Figure 3.4 shows annual vehicle sales by type and Figure 3.5 shows sales data weighted by fuel economy distribution for 1975 through 2008. Figure 3.6 shows the adjusted composite miles per gallon for the nine highest selling marketing groups that account for over 95% of all US sales. Only three of the groups (Toyota, BMW, and Chrysler) show a slight increase in average fuel economy since 1998 (EPA, 2008). For Model Year 2008 only Volkswagen and BMW had a market share for trucks that was less than 39%.



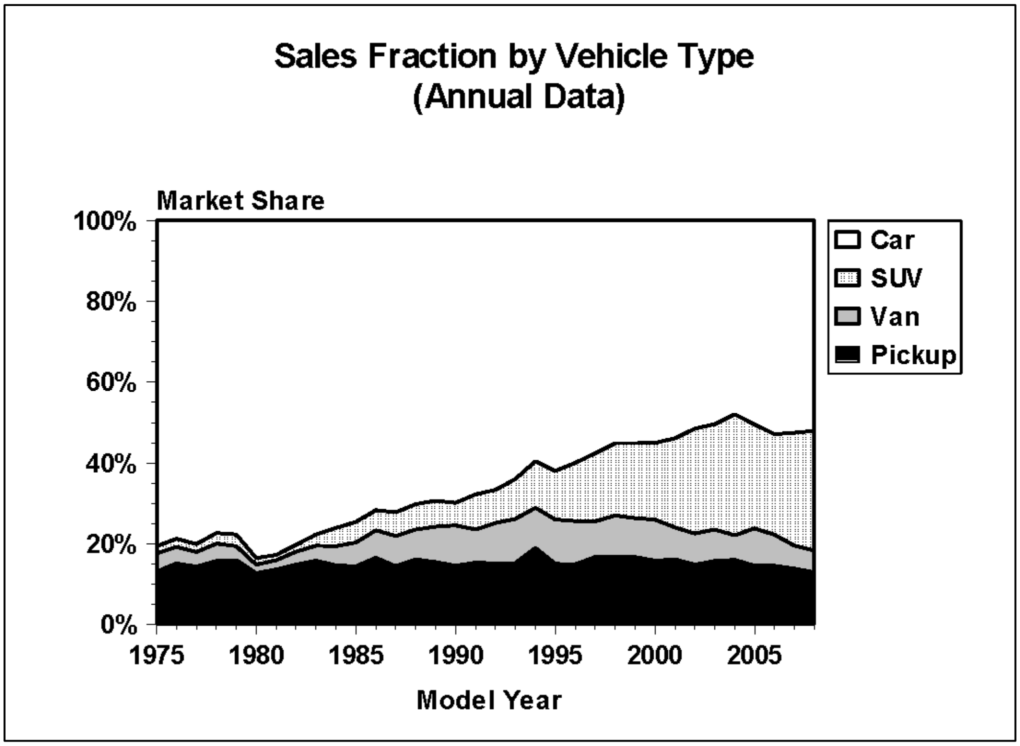
Source: EPA, 2008

Figure 3.2: CAFE Performance Passenger Cars 1978-2010



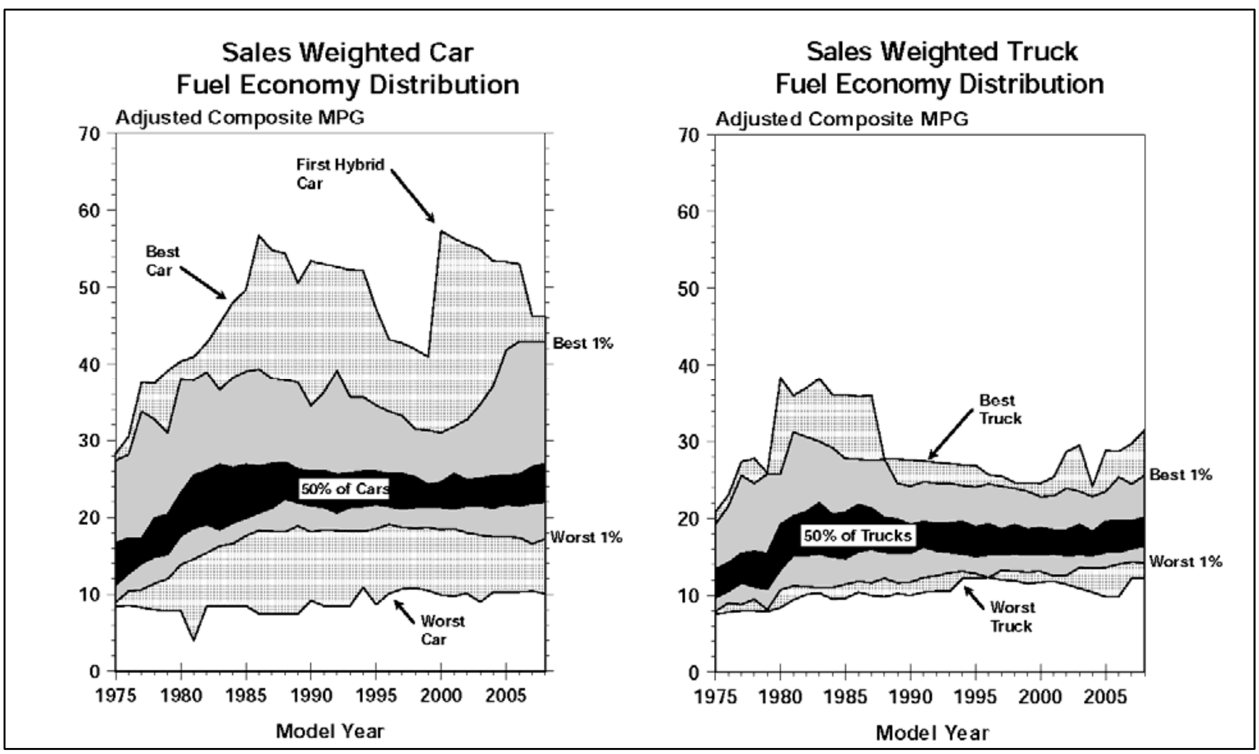
Source: EPA, 2008

Figure 3.3: CAFE Performance Light Trucks 1978-2010



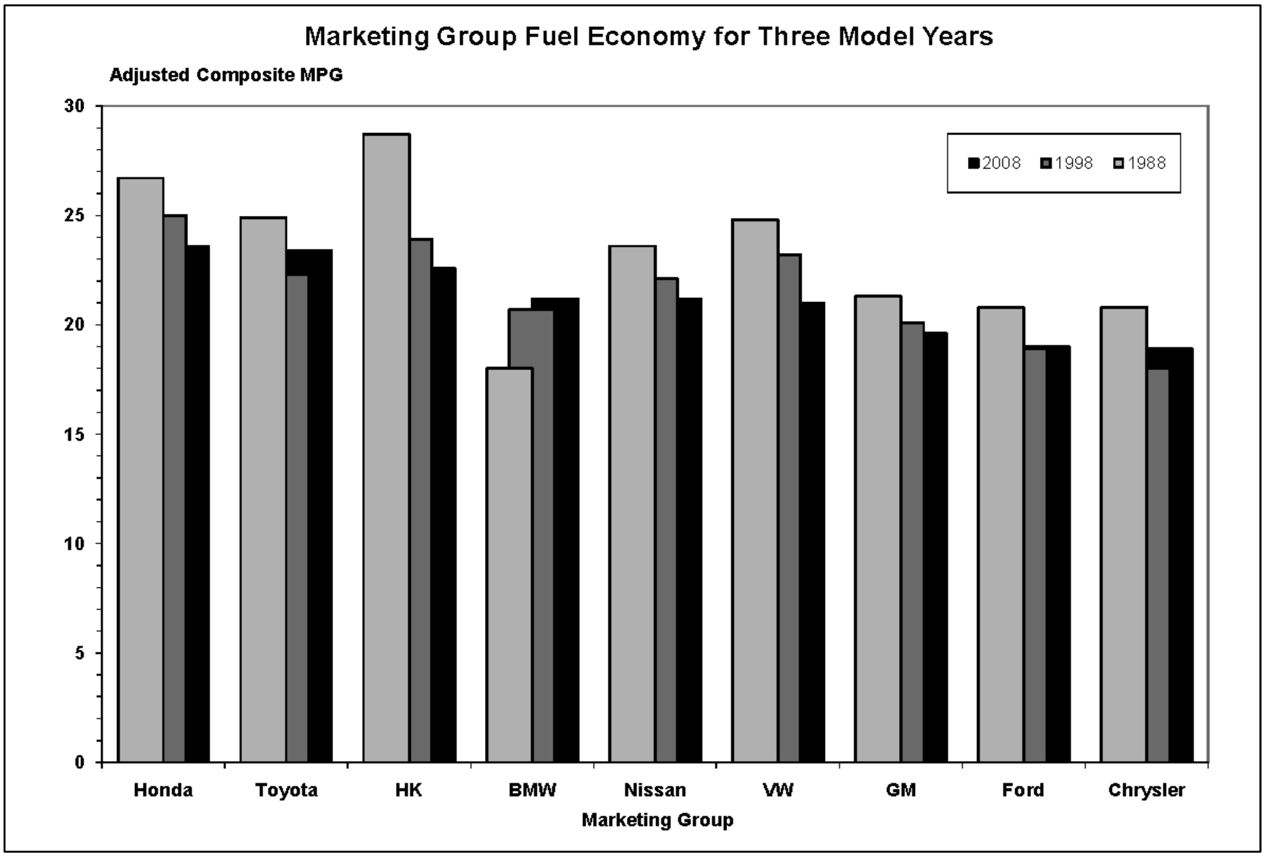
Source: NHTSA, 2009

Figure 3.4: US Annual Sales by Vehicle type 1975 -2007



Source: NHTSA, 2009

Figure 3.5: Sales Weighed Fuel Economy Distribution 1975- 2008



Source: EPA, 2008

Figure 3.6: Marketing Groups Fuel Economy for Three Model Years

CAFE also provides a credit system for manufacturers. Thus, if average fuel economy for a passenger car or light truck for a particular model year exceeds the standards, the manufacturers earn a credit (49 U.S.C §32903 9a)-(b)[6]. These credits can be applied to any three consecutive model years immediately prior to (known as *carry-back credits*) or adjacent (known as *carry-forward credits*) model year in which the credits are earned. The credits cannot be traded between manufacturers, or between fleets, e.g., between light trucks and passenger vehicles.

CAFE standards came back in play as global warming has begun to be been tackled by multiple cities, states, and stakeholders in the U.S. in response to the lack of action by the Bush administration. Given the make-up of the U.S. passenger fleet—which now includes SUVs and minivans—tightening CAFE standards is proposed by multiple groups as essential to reduce greenhouse gases (GHG) that contribute to global warming. Currently the U.S. is the largest emitter of GHG, although China was set to exceed the U.S. during the 2008/2009 period. According to Martel and Stelcen, "*proponents of this approach point out that while the program initially made a significant contribution to moderating fuel use, its impact has abated because*

[6] The amount of credit is determined by multiplying the tenths of a mile per gallon by which the manufacturer exceeds the standard for that model year, by the number of vehicles manufactured in that year.

the CAFE standards were frozen by Congress throughout much of the 1990's when sales of trucks, SUVs and minivans substantially increased."

Congress commissioned the National Academy of Sciences and the DOT to conduct a study to evaluate the effectiveness of CAFE standards in 2001. The National Academy created a Committee on the Effectiveness and Impact of CAFE standards to respond to the Congressional request. The committee released its report in 2002. The report found that while CAFE had contributed to improved fuel economy, making more stringent emission rules would not be an effective measure because other policies could accomplish the same outcome as reducing fuel consumption. The committee also noted that this would provide more flexibility to manufacturers and address inequities within the system. The committee listed multiple measures that policy alternatives, including tradable credits, fee-bates, vehicle attribute standards (e.g., vehicle weight size or payload), and most surprisingly, raising fuel taxes. The report also recommended phasing out credit for dual fuel vehicles, arguing that CAFE was not a good way to encourage the use of alcohol fuels (National Research Council, 2002).

New rules issued in 2004 required all new passenger vehicles (including SUVs, pick-up trucks, and minivans) to meet more stringent tailpipe emission standards. This was achievable because of the introduction of low sulfur gasoline and diesel (in 2006) and a new generation of sophisticated emission control devices and catalytic converters that had been developed by the motor manufacturing industry.

After the 2002 Committee's Report's comment period, the DOT proposed reforming the CAFE program. In August 2005 it announced that by 2011 all manufacturers would be required to comply with a new 'reformed CAFE' standard. Under this program the standards were restructured so that they were based on measuring a vehicle's footprint (size) by multiplying its wheelbase by its track width. Six footprint categories were created with target fuel economy levels. EPA issued a final rule to implement these reforms in March 2006. Immediately after this, however, nine states, the District of Columbia, New York City, and four public interest organizations[7] filed suit in the U.S. Court of Appeals for the 9th Circuit against these proposed changes. According to New York Attorney General:

> "At a time when consumers are struggling to pay surging gas prices and the challenge of global climate change has become even more clear, it is unconscionable that the Bush Administration is not requiring greater mileage efficiency for light trucks. NHTSA failed to consider alternative approaches that would have promoted energy conservation, made meaningful contributions to increased fuel economy and encouraged technological innovation. NHTSA failed, in all respects, to consider the environmental consequences of its proposed overhaul of light truck standards, failed to consider the changes in the environment since its last Environmental Impact Statement in the 1980s, and failed to evaluate the impact of CO_2 emissions despite identifying the threat of CO_2 and global climate change as new information concerning the environment. The standards, which shift the mile-per-gallon requirements from a fleet-wide basis to a new structure based on weight categories, create incentives to build larger, less fuel-efficient models, which will jeopardize air quality and the climate." (New York Attorney General, 2006)

[8] The nine states were Connecticut, Maine, Massachusetts, New Jersey, New Mexico, New York, Oregon, Rhode Island, and Vermont. The public interest groups were Sierra Club, Environmental Defense, Natural Resources Defense Council, and Center for Biological Diversity.

On November 15, 2007, the 9th Circuit found in favor of the petitioners by voiding the proposed CAFE standards for light trucks for 2008–2011 (Center for Biological Diversity v. National Highway Transportation Safety Administration (F3d, 2007 WL 3378240 9th Cir. Nov. 15, 2007). In making its ruling, the court also followed the recently decided Supreme Court decision Massachusetts v. EPA regarding GHG emissions. The court held:

> NHTSA's failure to monetize the value of carbon emissions in its determination of the MY 2008-2011 light truck CAFE standards, failure to set a backstop, failure to revise the passenger automobile/light truck classifications, and failure to set fuel economy standards for all vehicles in the 8,500 to 10,000 lb. GVWR class, was arbitrary and capricious and contrary to the EPCA. We therefore remand to NHTSA to promulgate new standards consistent with this opinion as expeditiously as possible and for the earliest model year practicable… We also hold that the EA was inadequate and Petitioners have raised a substantial question as to whether the Final Action may have a significant impact on the environment. Thus, we remand to NHTSA for the preparation of a full EIS.

Meanwhile, in the Energy Independence & Security Act of 2007 (P.L. 110-140), Congress required the administration to raise CAFE standards to a minimum of 35 mpg by 2020. In April 2008 NHTSA set out new standards for Model Years 2011-2015 that would result in a fleetwide average of 31.6 mpg

The argument surrounding fuel efficiency did not end with this new standard setting. NHTSA relied on Energy Information Administration (EIA) projections of gasoline averaging $2.42 a gallon in 2016. In June 2008 Chairman Edward Markey of the House Select Committee on Energy Independence and Global Warming joined 44 other members of Congress to pen a letter to the EPA Administrator criticizing the "absurd" assumptions about gasoline prices that were being used for proposing new fuel economy rules for automobiles. "*The National Highway Traffic Safety Administration based its proposed regulations using EIA assumptions about gas prices that defy reality.*"[8] Markey noted that: "*NHTSA's reliance on these highly unrealistic projections have the effect of artificially lowering the calculated maximum feasible fuel-economy standards that NHTSA is directed by law to promulgate.*" Markey's letter argued that "*NHTSA's final fuel-economy regulations must be based upon realistic and rational gas price assumptions*" (AASHTO, July 2008).

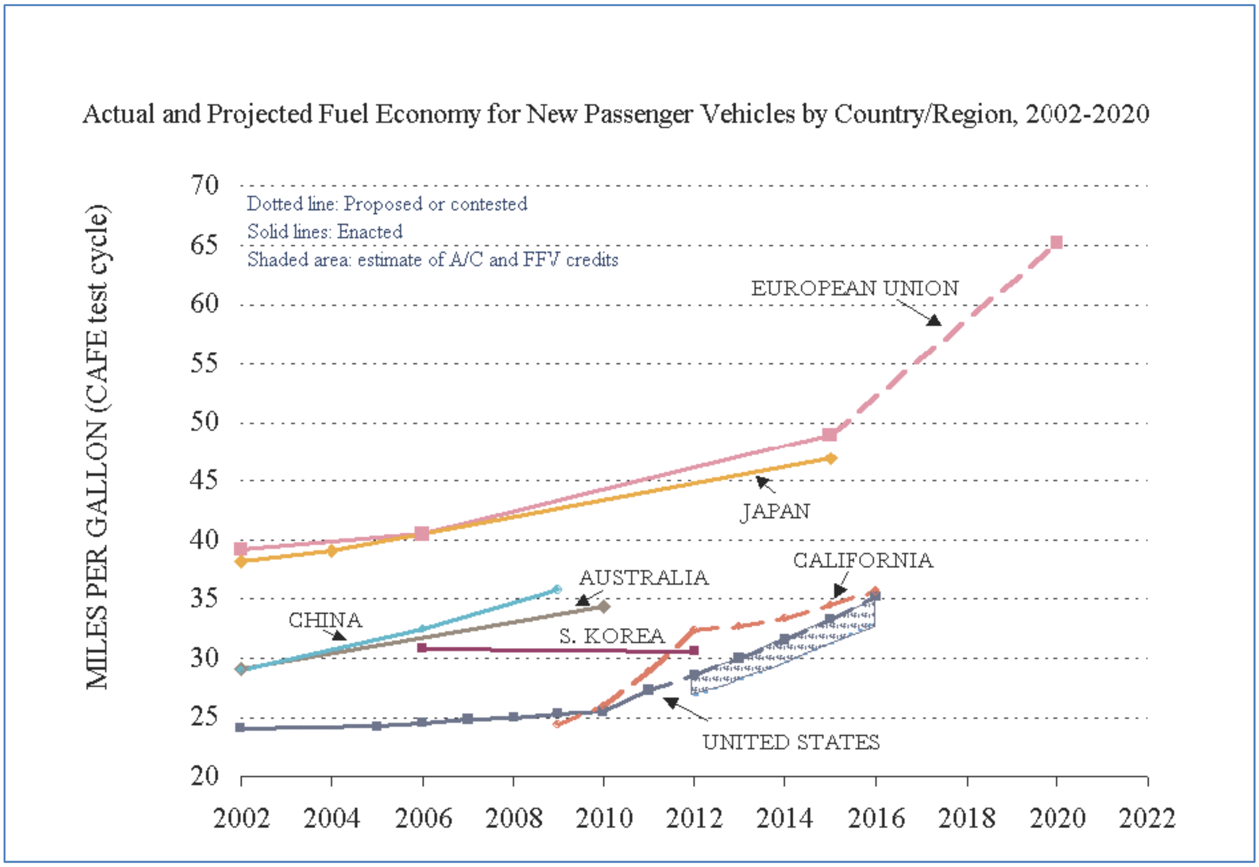
The Select Committee met on June 26, 2008 to examine NHTSA's proposed new fuel economy standards. In the opening remarks to this hearing, Chairman Markey noted that technology was available to cost-effectively achieve 35 mpg by 2015. Markey urged NHTSA to redo its analysis using higher gasoline price estimates, which would produce a higher feasible target for 2015. The Acting Under-Secretary for the DOT told the committee that the standards proposed would increase fuel economy 4.5% per year over the five-year period and that passenger cars would have to reach an average of 35.7 mpg and light trucks 28.6 mpg (AASHTO, 2008).

The CAFE story does not end here. The incoming Obama administration announced a new policy in May 2009 known as the National Fuel Efficiency Policy. This was aimed to reduce greenhouse gas emissions and improve fuel economy. A notice of proposed rulemaking was

[8] The average price of regular unleaded in the U.S., according to AAA, was $4.09 a gallon the first week of July 2008.

issued by NHTSA and EPA jointly in the federal register on September 28, 2009 (Federal Register, 2009) to begin the process of implementing this new program.

To provide a comparator regarding fuel economy and GHG emissions, Figure 3.7 shows how the U.S. ranks for fuel economy compared to the rest of the world, using data compiled by the International Council on Clean Transportation (ICCT). Figure 3.7 reflects current administration targets.



Source: ICTT, 2009

Figure 3.7: Actual and Projected Fuel Economy for New Passenger Vehicles by Country/Region 2002-2020

3.2.2 Heavy-Duty Trucks

There are no CAFE standards for the heavy-duty fleet in the United States. Table 3.2 shows the fuel efficiency of heavy single unit trucks between 1980 and 2002.

Table 3.2: Fuel Efficiency of Heavy Single Unit Trucks 1980-2002[9]

Year	Registration (thousands)	Fuel Use	Fuel efficiency mpg	VMT (million miles)
1980	4,374	6,923	5.8	39,813
1981	4,455	6,867	8.8	39,568
1982	4,325	6,803	6.0	40,658
1983	4,204	6,965	6.1	42,546
1984	4,061	7,240	6.1	44,419
1985	4,593	7,399	6.1	45,441
1986	4,313	7,386	6.2	45,637
1987	4,188	7,523	6.4	48,022
1988	4,470	7,701	6.4	49,434
1989	4,519	7,779	6.5	50,870
1990	4,487	8,357	6.2	51,901
1991	4,481	8,172	6.5	52,898
1992	4,370	8,237	6.5	53,874
1993	4,408	8,488	6.7	56,772
1994	4,906	9,032	6.8	61,284
1995	5,024	9,216	6.8	62,705
1996	5,266	9,409	6.8	64,072
1997	5,293	9,576	7.0	66,893
1998	5,414	9,741	7.0	67,894
1999	5,763	9,372	7.5	70,304
2000	5,926	9,563	7.4	70,500
2001	5,704	9,667	7.5	72,448
2002	5,654	10,305	7.4	75,887

Source: Apostolides, 2009

Table 3.3 shows the fuel efficiency of combination trucks for the same time period. Fuel efficiency for heavy single unit trucks increased by almost two miles to the gallon during this time period.

[9] Includes all single unit trucks with two or more axles or more than four tires

Table 3.3: Fuel Efficiency of Combination Trucks 1980-2002[10]

Year	Registration (thousands)	Fuel Use	Fuel efficiency mpg	VMT (million miles)
1980	1,417	13,037	5.3	68,674
1981	1,261	13,509	5.1	69,134
1982	1,265	13,583	5.2	70,765
1983	1,304	13,796	5.3	73,586
1984	1,340	14,188	5.5	77,377
1985	1,403	14,005	5.6	78,063
1986	1,408	14,475	5.6	81,038
1987	1,530	14,990	5.7	85,495
1988	1,667	15,224	5.8	88,551
1989	1,707	15,733	5.8	91,879
1990	1,709	16,133	5.8	94,341
1991	1,691	16,809	5.7	96,645
1992	1,675	17,216	5.8	99,510
1993	1,680	17,748	5.8	103,116
1994	1,681	18,653	5.8	108,932
1995	1,696	19,777	5.8	115,451
1996	1,747	20,192	5.9	118,889
1997	1,790	20,302	6.1	124,584
1998	1,831	21,100	6.1	128,159
1999	2,029	24,537	5.4	132,384
2000	2,097	25,666	5.3	135,020
2001	2,154	25,512	5.4	136,584
2002	2,277	26,451	5.2	138,643

Source: Apostolides, 2009

3.3 Air Quality and Emissions

3.3.1 The Clean Air Act

The Clean Air Act 1970 (as amended) lays out the landscape for regulatory review of emissions from non-point sources (vehicles). More recently, the applicability of the legislation to greenhouse gas emissions, according to Martel and Stelcen (2007), has been a focus of debate and litigation. With multiple proponents seeking more robust federal action in this arena and other litigants utilizing the preemption provisions of the federal legislation—which prohibit state regulation of vehicle emissions—to continue to block state regulation of greenhouse gases from vehicles. With the Obama administration elucidating a new stance with regards to global warming and the environment—including the appointment of a Secretary of Environment who is a scientist with a novel laureate in physics—this landscape make look dramatically different for vehicle operating costs in a few years.

[10] Combination trucks include all trucks designed to be used in combination with one or more trailers

While the Clean Air Act (CAA) of 1970 is viewed as the starting point for federal air pollution controls within the U.S., air pollution had previously been identified as a national problem in the Air Pollution Control Act of 1955 (which provided for federal research programs to investigate pollution and its health and welfare effects). This act was put in place after many state and local governments had already instigated their own legislation. This was replaced with the Clean Air Act of 1963. This Act focused on reducing and improving air pollution at the state and local level (Gerard, 2007). It granted $95 million over a 3-year period to state and local governments and air pollution control agencies to conduct research and create control programs. The act also recognized for the first time the dangers of motor vehicle exhaust, and *encouraged* the development of emissions standards from these non-point sources. This act was amended in 1965 by the Motor Vehicle Air Pollution Control Act, which sought to establish further standards for automobile emissions. The 1963 CAA was entirely rewritten in the 1970 CAA, however, and adopted a cooperative federalism approach to address failures in prior guidance. The 1970 CAA focused on pollutants identified as having direct human health effects. Areas that were in non-attainment were required to produce an emissions inventory for each pollutant that violated the mandated standards and bring the National Ambient Air Quality Standards (NAAQS) into conformity through the use of State Implementation Plans (SIPs).

3.3.2 1990 CAA Amendments

In 1990, the Clean Air Act (CAA) was amended after a decade of virtual inactivity. President George H.W. Bush proposed new revisions that built on congressional proposals that had been proposed and advanced during the 1980s. At this stage too, President Bush was aware of the Bruntland Report released in 1982, and was contemplating his legacy as the 1992 Rio Conference on the Environment and Development was beginning to loom on the horizon. Diplomats spent 2 years prior to the conference drafting the various treaties, instruments, and other initiatives and the U.S. was heavily involved in negotiating and developing these. It was also at this time point that the hole in the ozone layer over Antarctica was discovered and when "global warming" began to enter the vernacular. The amendments were passed overwhelmingly in both chambers (401-21 in the House and 89-11 in the Senate). After emerging from a joint conference committee President Bush signed the bill into law on November 15, 1990.

Breakdown of the 1990 Amendments

New themes that were embodied within the changed act vis-à-vis motor vehicles included:

- Encouraging the use of market-based principles, innovative approaches and performance-based standards, and emission banking and trading
- Developed a framework for alternative fuels use (with a California pilot program)
- Reduce energy waste and create market for clean fuels derived from grain/natural gas

The Act contained nine titles: (Title I—Provisions for Attainment and Maintenance of National Ambient Air Quality Standards; Title II—Provisions Relating to Mobile Sources; Title III—Air Toxics; Title IV—Acid Deposition Control; Title V—Permits; Title VI—Stratospheric Ozone and Global Climate Protection; Title VII—Provisions Relating to Enforcement; Title VIII—Miscellaneous Provisions; Title IX—Clean Air Research).

The amendments substantially added elements to the pre-existing law, as well as adding specific new requirements for State Implementation Plans, mandating that every area in the U.S. had to meet specific standards for six criteria pollutants: ozone, carbon monoxide, nitrogen dioxide, sulfur dioxide, lead, and particulate matter (that had an aerodynamic diameter that less than 10um and 2.5um). The amendment also created a new Title V Operating Permit Program. This stipulated new requirements for fuels and motor vehicles as well as non-road engines. The Amendments also required seven metropolitan areas with the worst ground-level ozone to use reformulated gasoline. The District of Columbia and 17 other states also chose to use reformulated gasoline. The Act also clarified how areas were to be designated and re-designated as 'attainment' and gave EPA authority to define boundaries for non-attainment areas.

Title II is the main title for the purposes of vehicles. The amended act established tighter pollution standards for emissions from automobiles and trucks. Congress made significant changes to the motor vehicle provisions of the Act in this amendment because of the unforeseen growth in auto emission in many urban areas, combined with the serious air pollution that was occurring in many U.S. urban areas.

The 1990 amendments established much tighter pollution standards for emission from automobiles and trucks. These included reduced tailpipe emissions of hydrocarbons, carbon monoxide, and nitrogen oxides. These were placed on a phase-in schedule that was to begin with model year 1994. Auto manufacturers were also required to reduce vehicle emissions that resulted from the evaporation of gasoline during refueling. The act allowed the Secretary of Transportation to revise standards for heavy duty trucks for model year 1998 and to reduce NO_x emissions to not exceed 4.0 grams per brake horsepower hour.

Fuel quality was also controlled. Reductions were required by schedule for gasoline volatility and the sulfur content of diesel. A new program for reformulated gasoline was initiated in 1995 for nine cities with the worst ozone problems. Other cities were also allowed to opt into the reformulated gasoline program. Under this program, higher levels (2.7%) of alcohol-based oxygenated fuels were to be produced and sold in 41 areas during the winter months that exceeded the federal standard for carbon monoxide. The new law also established a clean fuel car pilot program in California, which required the phase-in of tighter emission limits for 150,000 vehicles in model year 1996 increasing up to 300,000 units by 1999. This could be met with any combination of vehicle technology or cleaner fuels. Other states were also allowed to opt into this program, but only through incentives, not through any sales or production mandates. The law also required 26 of the dirtiest areas of the country to adopt a program limiting emission from centrally fueled fleets of 10 or more vehicles beginning in 1998.

Congress also required conformity under the 1990 amendments in Title I. So transportation projects could not be federally funded or approved if they did not align with state air quality goals. Also, new transportation projects could not cause or contribute to new violations of the air quality standards, worsen existing violations, or delay attainment of the new standards.

3.3.3 Regulation of Lead and Other Toxic Pollutants under CAA

Under the CAA, EPA has issued rules to regulate pollutants from vehicle exhausts, refueling stations and the evaporation of gasoline. Today's emissions are estimated by EPA (EPA, Key Elements) to be over 90% cleaner than their predecessors. The most important of EPA's early accomplishments was the elimination of lead from gasoline, which began in the mid 1970s. The elimination of lead allowed catalytic converters to be installed on all new vehicles.

The 1990 CAA amendments banned lead in gasoline and by 1996 all leaded gasoline was banned in the U.S. Table 3.4 shows estimated national average vehicle emission rates of heavy and light duty vehicles from 1990-2007.

Table 3.4: Estimated National Average Vehicle Emission Rates

	1990	2000	2006	2007
Gasoline (assuming zero reformulated gasoline)				
Cars				
Exhaust HC	2.79	0.97	0.46	0.42
Non-exhaust HC	1.21	0.92	0.68	0.62
Total HC	**3.99**	**1.89**	**1.13**	**1.04**
Exhaust CO	42.89	18.53	10.87	10.28
Exhaust NO_X	2.70	1.29	0.79	0.73
Light trucks				
Exhaust HC	3.687	1.45	0.69	0.64
Non-exhaust HC	1.36	0.97	0.71	0.66
Total HC	**5.04**	**2.42**	**1.40**	**1.31**
Exhaust CO	56.23	26.81	14.33	13.52
Exhaust NO_X	2.62	1.54	1.09	1.02
Heavy trucks				
Exhaust HC	3.66	1.22	0.53	0.48
Non-exhaust HC	2.74	1.62	1.14	1.07
Total HC	**6.40**	**2.84**	**1.67**	**1.54**
Exhaust CO	85.61	31.08	14.51	13.55
Exhaust NO_X	7.19	5.26	3.73	3.33
Diesel				
Cars				
Exhaust HC	0.68	0.80	0.48	0.36
Exhaust CO	1.49	1.78	1.41	1.21
Exhaust NO_X	1.83	1.81	1.11	0.85
Light trucks				
Exhaust HC	1.59	1.02	0.79	0.63
Exhaust CO	2.67	1.77	1.34	1.06
Exhaust NO_X	2.71	1.76	1.30	1.09
Heavy trucks				
Exhaust HC	2.21	0.79	0.51	0.48
Exhaust CO	10.06	4.10	2.90	2.66
Exhaust NO_X	23.3.4	18.05	10.55	9.60
Key: CO = carbon monoxide; HC = hydrocarbons; NO_X = nitrogen oxides				

Source: Freight Facts and Figures 2008

Under the CAA certain metropolitan areas that have the worst ground-level ozone are required to use reformulated gasoline to reduce the pollution. EPA assisted the 17 states and DC district in their use of reformulated gasoline, which not only reduces ozone but also other toxic air pollutants including benzene and pollutants that contribute to making smog.

Another component within CAA's 1990 amendments was the introduction of low sulfur fuels, and most importantly ultra low sulfur gasoline (ULSG). In 2006 refiners began to supply gasoline with lower sulfur levels: up to a 90% reduction. Sulfur affects the catalytic converter's ability to clean-up exhaust output. New technology developed to monitor emissions in vehicles was extremely sensitive to the sulfur content so reducing it became a priority for EPA to ensure that emissions control devices continued to be effective in controlling and eliminating tail-pipe pollutants. The next step was to reduce sulfur in diesel with the use of ultra low sulfur diesel (ULSD). This was also because of the introduction of new technology in heavy duty diesel engines to reduce pollutants, specifically particulate matter and NO_2. The refiners began delivering ULSD in 2006 and in 2007 ULSD became available for off-road diesel engines.

EPA has also set up the Federal Clean Diesel Program in 2001. Under this program, EPA will award grants to assist eligible fleet candidates to achieve voluntary emission reductions. These include buses, heavy duty trucks, vehicles used in construction, marine engines, locomotives, or non-road engines, and those involved in handling of cargo. The clean diesel program can be found at EPA's website at www.epa.gov/cleandiesel.

EPA utilizes a series of models to assess, as well as estimate, emissions from point-source and non-point sources. The MOBILE model accounts for 28 vehicle types operating on four roadway types under a range of conditions.

3.3.4 Changes to Particulate Matter Standards

In 1987 EPA established standards for particulates under 10 microns (PM_{10}) and for fine particles smaller than 2.4 microns ($PM_{2.5}$). Particulates are one of the criteria pollutants under NAAQS. These standards were revised in 1987 and in 2006. The EPA's previous review and establishment of particulate NAAQS had been the subject of litigation and challenges including a Supreme Court decision in 2001 (American Trucking Associations v. EPA 174 F.3d 1027, 1055-56 (D.C., Cir 1999).

The 2006 revisions were based on a statutorily required period review that based its findings on scientific studies available from 1997 and 2002. The 2006 standards "generally tighten the air quality standards for particulate matter" (Esworthy et al., 2007). The primary NAAQS for PM2.5 and PM10 include an annual and a daily (24 hour) time limit. To attain the annual standards, the three-year average of the weighted annual arithmetic mean PM concentration at each monitor must not exceed the maximum limit set by the agency (EPA Website). Table 3.5 shows the 2006 final revisions and previous promulgated NAAQS.

Table 3.5: NAAQS Standards for Particulate Matter

	Previous NAAQS	EPA Final 2006 NAAQS
	$PM_{2.5}$ (Fine)	
24-Hour Primary Standard	65 µg/m3	35 µg/m3
Annual Primary Standard	15 µg/m3	15 µg/m3
	PM_{10} (Coarse)	
24-Hour Primary Standard	150 µg/m3	150 µg/m3
Annual Primary Standard	50 µg/m3	Revoked

Source: Elsworthy et al., 2007

However, immediately after these were released 13 states and the District of Columbia petitioned the court of Appeals to review the 2006 particulate NAAQS (the cases were consolidated with American Farm Bureau Federation V. U.S. EPA No. 06-1410 (D.C. Cir, 2006). The case was decided February 24, 2009. The court held:

> Because the agency promulgated standards for fine particulate matter that were, in several respects, contrary to law and unsupported by adequately reasoned decision making, we grant the petitions for review in part and remand those standards to the agency for further proceedings. We deny the petitions for review of the agency's standards for coarse particulate matter because those standards are not arbitrary, capricious, or otherwise contrary to law.

On January 15, 2009, the EPA proposed revisions to the index that reports significant harm level for particle pollution; states use this index to report daily concentrations for fine particle pollution, also known as PM2.5. The proposed changes would set a "significant harm level" for PM 2.5, which states use in developing emergency episode plans. EPA is currently seeking comments (EPA, Particulate Matter Website, 2009).

3.3.5 New Engine Rules

EPA has also put out new rules regarding multiple types of engines in 2007. For on-road motor vehicles, in January 2007 EPA proposed amendments to the Clean Diesel Trucks and Buses Program, which requires advanced emission control systems for highway engines used in vehicles over 14,000 pounds. The amendments required installation of onboard diagnostic systems that monitor emissions and alert operators on the need for repairs. The program also revised existing onboard diagnostic requirements for diesel engines that were used in heavy-duty vehicles under 14,000 pounds.

In February 2007 EPA finalized rules that limited the amount of benzene content in gasoline, which limited hydrocarbon emissions from passenger vehicles and established evaporative emission standards for passenger vehicles. In April 2007 the EPA proposed to expand a temporary provision that allowed all-terrain vehicle manufactures to certify compliance with new emission standards using a steady-state engine-based duty cycle rather than a chassis-based federal test procedure, through to the 2015 model year.

In May 2007 EPA proposed amendments to the transportation conformity program to make it more consistent with the CAA. Part of the proposal would allow state and local governments to have more time to meet conformity obligations, as well as allowing state DOTs to make 'hot-spot' findings in CO_2 non-attainment and maintenance areas. This followed on from a case in 2006, Environmental Defense v. EPA, where petitioners had argued that the rules' requirement that a project not cause or contribute to new violations or increase the severity of existing violations did not incorporate all the criteria under Section 176(c)(1)(a)-(b) (Environmental Defense v. EPA 509 F.3d 553 (D.C Cir. 2006).

In May 2007 EPA also published a final rule regarding the renewable fuel program. This was to ensure that the total volume of renewable fuels used in gasoline each year met the requirements of the Energy Policy Act of 2005. It established renewable fuel usage standards for refiners, blenders, and importers of gasoline. It identified renewable fuels that qualified for compliance. It also established a fuel trading program

EPA also issued new rules for emissions for heavy-duty fleets. Engines manufactured after 2010 will be required to reduce the amount of Nitrogen Oxide (NOx) allowed in emissions. These will drop by over 99% to 0.2 g/hp-hr. This will bring heavy-duty trucks to a nearly zero emission standards when combined with the reductions in soot and particular matter that were require for 2004 engines.

To achieve this, manufacturers are using a variety of technologies towards 2007 and 2010 compliance; these include diesel particulate filters, exhaust gas recirculation (EGR), and selective catalytic reduction (SCR). EGR has been admitted by manufacturers to "*not get them all the way to being 2010 compliant*" (Kress, 2008). Some manufacturers are indicating that they will use existing EPA credits so that they can meet the 2010 regulations. Table 3.6 shows the reductions in key heavy duty truck emissions.

Table 3.6: Reductions in Key Heavy-Duty Truck Emissions (g/hp-hr)

Year	HC	CO	NOx	PM
1988	1.3	15.5	10.7	0.60
1990	1.3	15.5	6.0	0.60
1991	1.3	15.5	5.0	0.25
1994	1.3	15.5	5.0	0.10
1998	1.3	15.5	4.0	0.10
2004		15.5	2.5	0.10
2007	0.14	15.5	1.2	0.10
2010	0.14	15.5	0.2	0.01

Source: Heavy Duty Trucking, 2008

3.3.6 Heavy-Duty Fleet Adaptations to New Rules

As a consequence of new clean air regulations (and throughout 2007-2008 higher gasoline and diesel prices) trucking companies have been adapting their business practices. A report in *Heavy Duty Trucking* in August 2008 showed that carriers were using standby electric reefers in an effort to comply with new CAA regulations (and new rules from the California Air Resources Board (CARB)) as well as reduce diesel costs to run reefers (Berg, 2008). One group, who had 288 older reefers, was planning to replace with new units that were more cost efficient than retrofitting units. Another option that is being used at ports and other trucking stops is the ability to plug into 'shore power'. However, the availability of such units is limited. CARB was attempting to help in this manner by offering grants to help defray costs of installation. Emissions-free cryogenic reefers are also now being developed by the major manufacturers to reduce CO_2 levels as greenhouse gas legislation is now considered to be imminent with the election of the Obama administration.

Another new product that has been developed is a hybrid system that will run the electrically powered cooling and heating units in reefers. These eliminate drive belts and other components. Some of these units have no batteries so they have to be plugged in. One food distributor found that these hybrid units could save 29,000 on maintenance hours at approximately $1.50 to $1.90 an hour based on running times (Berg, 2008). Savings apparently occur because the engine runs few hours compared to a regular diesel unit. At a gallon an hour, these hybrid vehicles also save fuel.

Some manufacturers are also looking at wind-powered reefer development. These units will use wind spun generators to charge batteries that power the reefer. These units would have two wind turbine generators placed on top of the tractors sleeper with the batteries placed under the trailer. An electrical cord would tie this equipment together. The main issue with such elements is the space that batteries would take up and the weight that this equipment would add to the vehicle, along with the effect on aerodynamics.

3.3.7 Litigation under CAA Provisions

Cases have been litigated regarding transportation conformity requirements. For example, in Environmental Defense v. EPA (509 F.3d 553 (D.C. Cir. 2007), environmental organizations petitioned for a review of the EPA final rule on hotspot analysis performed under transportation conformity requirements of CAA. The plaintiffs (petitioners) argued that the rule's requirement that a transportation project not cause or contribute to a new violation or increase in severity of existing violations failed to incorporate criteria under Section 176(c)(1)(a)-(b).

3.4 Alternative Fuels

During the past 25 years, alternative fuels mandates have also become a popular tool used by Congress and states to reduce emissions output. The Energy Policy Act of 2005 imposed Renewable Fuel standards (RFS) mandates of 7.5 billion gallons by 2012. President Bush enacted Executive Order EO 13432 (72 FR 27717, May 16, 2007) that created the "Twenty in Ten" program. The preamble of the press release noted the executive order was in response to the Supreme Court ruling in Massachusetts v. EPA, in which it ruled that the EPA must take action under the CAA regarding GHG emission from motor vehicles (Whitehouse, 2007).

Alternative fuels, however, have not necessarily created the panacea effect for which they were first touted. While ethanol was seen throughout the 2005 through 2007 period as the fuel of the future, its cost competitiveness could not match the spot price of gasoline up until 2005. Ethanol also suffered from a weak supply chain and distribution system. The supply chain network for ethanol was still in infancy and extremely reliant on the rail system as the pipeline network could not ship this corrosive fuel without retrofitting. There was also another issue that held back biofuels from taking market share: the dramatic need for destination terminals. Permitting for destination terminals was slow with many neighborhoods resisting the siting of new yards and increased rail activity.

Unfortunately, the rush to ethanol also had some unintended global consequences. What may have been the final nail in the coffin for biofuels over this short-term period was the impact that the shift to making ethanol from corn had upon the price of food and feedstocks. Riots were seen in many countries as the price of these commodities rose. The dramatic increase in the cost of corn led to a backlash against using a food staple for the food and feed industry to produce vehicular fuels (Monbiot, 2007).

As the price of fuel dropped during late 2008 and the recession kicked in, ethanol plants began to enter bankruptcy. Vera Sun, one of the nation's largest ethanol producers, announced in October 2008 that they had filed for bankruptcy (Galbraith, 2008). Any full-scale shift to biofuels will require major changes in the manufacture and distribution of the fuels, as well as continued supply of Flex-fuel vehicles.

3.5 The California Effect

Certainly, California has been the lead state that has attempted to push the barriers under the CAA, in terms of its ability to set environmental regulations that are more stringent than the federal government. At the time that the CAA was signed, California was the state that had set the tone in promulgating emissions reduction activity through a strict legislative code. In fact, California's activities and legislative agenda, in many instances, was the precursor that led to national standards being set for emissions reduction. California was allowed to pre-empt and set its own legislation, and was granted a waiver by the federal government for 'on-highway vehicles' regarding emissions.

CARB has set much of the agenda for the development of the legislation (in some cases preemptive) that California has enacted since 1990. This has included regulations and limitations for both point and mobile sources of pollutants and fuels. This has from time to time been litigated by the entities being regulated who have argued that the waiver was not exhaustive or exclusive, as well as the fact that the regulations were governed by sections of CAA that did not fall within the preemption waiver.

Notwithstanding litigation, CARB continues to roll out new rules regarding air quality and GHG emissions. For example, CARB is requiring that by December 2015 all 2008 truck model engines must be either replaced or retrofitted. However, standby electric units were able to quality as an alternative technology. So trailers could use Transportation Refrigerated Units that operated on electric standby during loading, unloading, and delivery times (CARB, Rule NO).

Litigation under CARB and California Provisions

As noted earlier there has been ample litigation against CARB and California legislation and policy setting rulings. For example, CARB set out limitations for diesel particulate matter from oceangoing vessels. This was litigated in Pacific Merchant Shipping Association v. Cackette. The eastern district court for California held that Section 209(e)(2) implies preemption for non-road vehicles and engines and this is broader than the express preemption for highway vehicles within CAA 209(e)(1).

Another example is Engine Manufacturers Association v. South Coast Air Quality Management District (498 F.3d 1031 (9th Cir. 2007). In this case the Engine Manufacturer's Association challenged a slew of fleet rules that South Coast Air Quality Management District adopted on the grounds that the regulations were preempted by the CAA. These required operators of certain vehicle fleets to choose vehicles meeting certain emission standards or contained specific alternative-fuel engines when vehicles were added to the fleet. This case was litigated all the way to the Supreme Court, which then remanded the case back to district court to review the status of preemption. On remand, back at district court, the regulations were held to not preempt CAA because the market participation doctrine allows state/local governments to impose emission standards more stringent than federal standards under CAA *to the extent* that they direct procurement behavior of state or local entities whose actions are proprietary. The United States Court of Appeals for the Ninth Circuit held that for the purposes of this doctrine, a state action was proprietary if it reflects the state's own interest in its efficient procurement of goods and services. The court upheld the regulations as they applied to the state and local governments, but remanded the case back to district court for further proceedings to determine which rules relating to non-state and local government entities are preempted.

Two other cases show how California has affected emissions regulations. First, Green Mountain Chrysler Plymouth Dodge Jeep v. Crombie (508 F.Supp. 2d 295 (D.Vt 2007) should be noted. This case was brought by representatives of the automotive industry regarding Vermont's motor vehicle GHG gas regulations, which they argued was preempted by federal fuel economy standards under the EPCA. This prohibits states regulating fuel economy standards. The district court held that if EPA were to grant a waiver under Section 209 of CAA for California's regulations on which Vermont's regulations were based, the waiver would convert the California and Vermont regulations into federal law, and thus California's rules were not expressly preempted. The District Court also held that, in the alternative, the California/Vermont regulations were not necessarily fuel economy standards, because GHG reductions could be achieved through other approaches and were therefore not preempted. The Court also held that California's rules did not conflict with federal law under EPCA.

Second, Central Valley Chrysler-Jeep Inc. v. Witherspoon (No CV F04-6663 AWI LJO, 2007 WL 135688 (E.D. Cal. Jan. 16, 2007)) also focused on California state regulations. Here, an affiliation of automotive manufacturers sought injunctive and declaratory relief to enjoin (stop) enforcement of California state regulations limiting GHG emissions from automobiles. Again, the plaintiffs alleged the regulations were preempted by EPCA and the foreign policy powers of the federal government. The court dismissed the claims on summary judgment, holding that California has the power to regulate GHG emissions, through its Section 209 waiver process. The court also noted that California's regulations were based on concerns for public health and welfare, and were not preempted by EPCA, which requires NHTSA to establish fuel economy standards. The court also found that plaintiffs had failed to establish that the regulations would conflict with federal foreign policy.

Litigation continues in this area. On September 8, 2009, the U.S. Chamber of Commerce and National Automobile Dealers Association filed suit to try and block California from implementing its own, stronger than national GHG standards for cars and trucks. California had finally been issued a waiver by EPA (refused by the Bush Administration) under the CAA to implement these new stricter standards. The Obama administration issued the waiver as it had announced the National Fuel Efficient Policy which would adopt uniform federal standards to reduce GHG emissions and increase the fuel economy for cars and trucks for model years 2011–2016, which would be in-line with the proposed California standards.

3.6 Greenhouse Gas Legislation

Finally, the emissions front is also now being tackled from another direction—specifically GHG emissions, which contribute to global warming.

In 1999, groups petitioned EPA to regulate certain greenhouse gases (GHG) from new motor vehicles under EPA's mandatory authority under CAA §202 (a) (1). The Clinton administration did not rule on the matter. In September 2003 the Bush administration denied the petitioners, arguing that EPA could not regulate GHG emissions from motor vehicles. This was challenged in 2005 in the Court of Appeals for the DC Circuit (which has jurisdiction over CAA matters). The case is well known: Massachusetts v. EPA (415 F.3d 50). The court found in EPA's favor and held that EPA's denial of petition was proper. The court denied the petitioner's appeal for rehearing in December 2005 and in 2006 this case reached the United States Supreme Court. In an eagerly anticipated ruling in 2007 the U.S. Supreme Court in a split 5-4[11]/[12] decision found in favor of petitioners and noted that "because greenhouses gases fit well within the Act's capacious definition of air pollutant, EPA has statutory authority to regulate emission of such gases from new motor vehicles" (Massachusetts v. EPA 549 US 497 (2007)). The Supreme Court in its ruling noted that global climate change was "the most pressing environmental challenge of our time." The court held that Congress had ordered the EPA to protect the state, and that the risk of harm was actual and imminent and therefore the state had standing to bring this challenge. The court finally held that the EPA had not provided a valid rationale for declining to regulate, and it remanded the rule back to the EPA.

The U.S. Congress has also been involved in proposing new legislation regarding climate change. Twelve bills were placed into the 110th Congress that related to climate change. The 111th session has proved to be no less fertile, with multiple bills being placed before Congress. Congress as expected took up the mantle of climate change legislation after the Presidential Election in 2008.

Figure 3.8 shows actual and projected GHG emission for new passenger vehicles using data compiled by the International Council on Clean Transportation (ICCT).

[11] Justice Stevens delivered the opinion of the court and was joined by Breyer, Ginsburg, Kennedy, and Souter.

[12] No surprises here—Justices Alito, Scalia, and Thomas joined Chief Justice Roberts in dissent. As is often the case Roberts filed a dissenting opinion in which Alito, Scalia, and Tomas joined and then Justice Scalia also filed his own dissenting opinion to which Roberts, Thomas, and Alito joined.

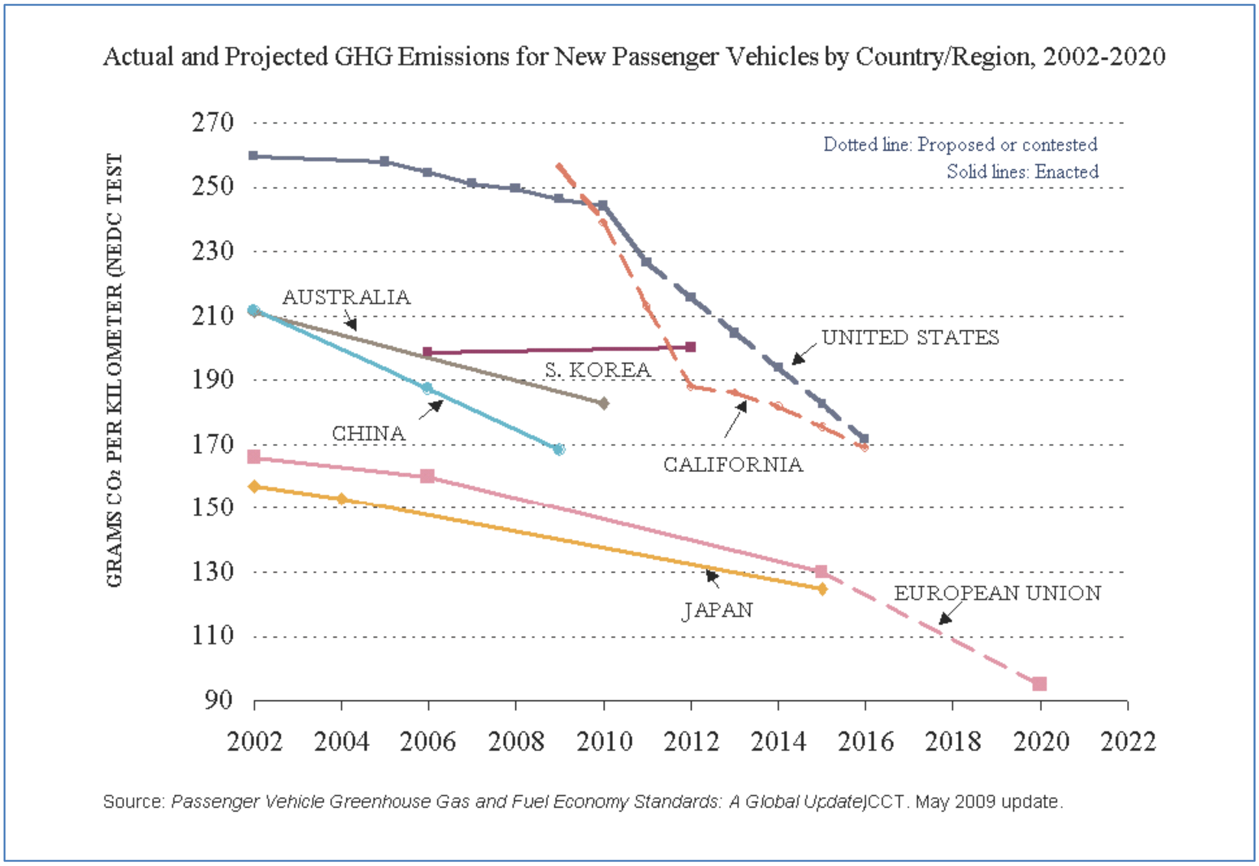


Figure 3.8: Actual and Projected GHG Emission for New Passenger Vehicles by Country/Region 2002-2020

3.6.2 State GHG Activities

Because of the lack of direction during the Bush Administration years, many states also set up entities and initiatives to address climate change and GHG emissions. Figure 3.9 shows various state initiatives that have been created top address the climate change issue.

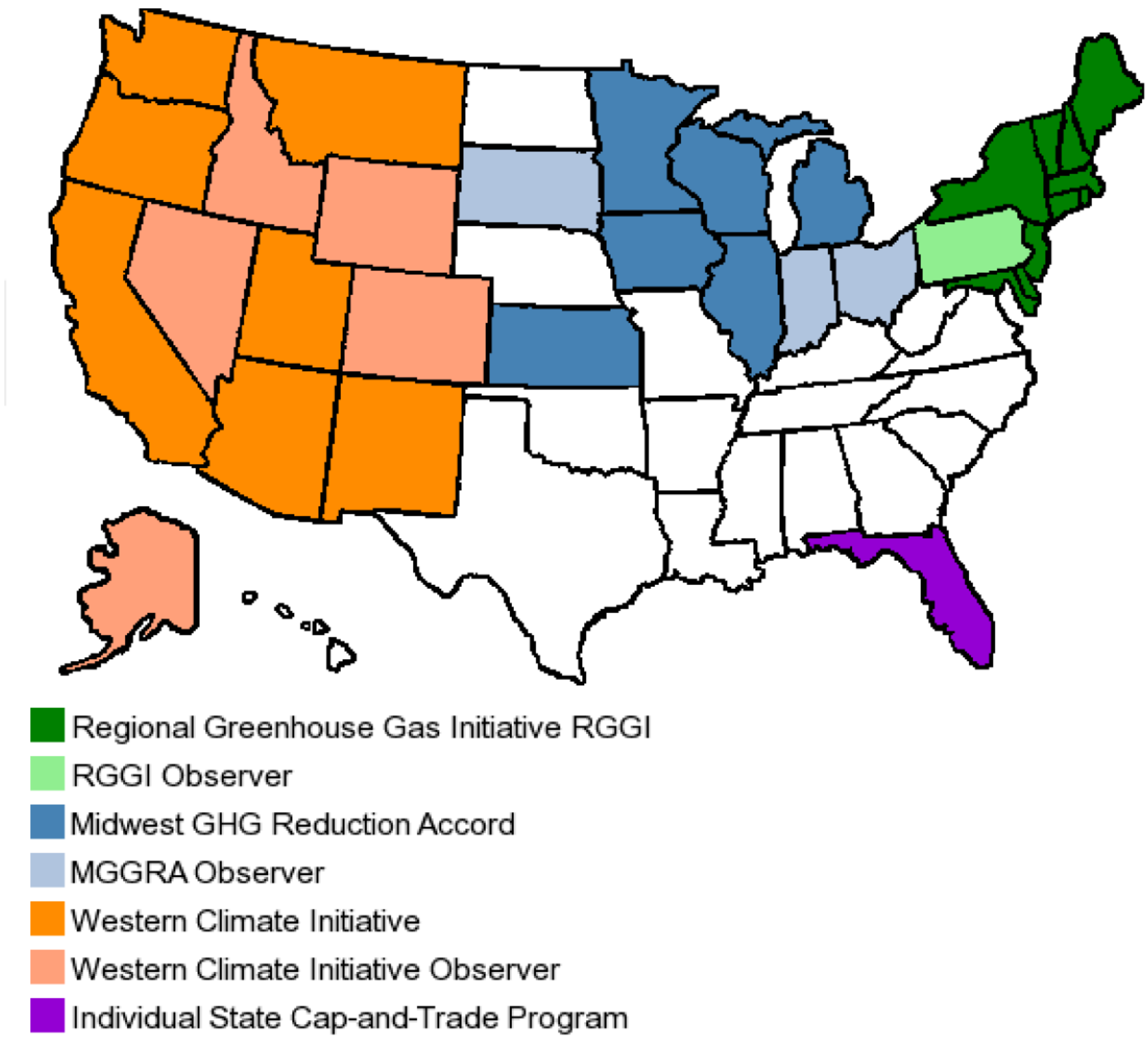


Figure 3.9: State GHG Initiative Groups

The most interesting of these initiatives is the Regional Greenhouse Gas Initiative (RGGI). The RGGI is an initiative of the Northeast and Mid-Atlantic States with the goal to reduce CO2 emissions from electric generating units 10% below 2009 levels by 2018 (the ten participating states are Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Rhode Island, and Vermont). RGGI is a non-profit corporation created to support development and implementation of the ten member states' CO2 budget trading programs. Then ten budget trading programs are implemented through state regulations and are linked through CO_2 allowance reciprocity. The ten individual state programs function as a single regional compliance market for carbon emission, in which the RGGI non-profit holds the auctions to trade these allowances. The program has just completed its fifth CO_2 allowance auction. A sixth will be held in December 2009.

As can be seen from Table 3.7, this is a robust trading market, with clearing prices averaging over the $2-3 range per unit. Table 3.8 shows the cumulative allowances sold and the proceeds yielded by each of the participating states.

Table 3.7: CO2 Auctions Conducted by RGGI

Auction Number & Date	Auction Format	Allocation Year	Quantity Offered	Quantity Sold	Clearing Price
I: 9/25/2008	Sealed Bid, Uniform Price	2009	12,565,387	12,565,387	$3.07
II: 12/17/2008	Sealed Bid, Uniform Price	2009	31,505,898	31,505,898	$3.38
III: 3/18/2009	Sealed Bid, Uniform Price	2009 2012	31,513,765 2,175,513	31,513,765 2,175,513	$3.51 $3.05
IV: 6/17/2009	Sealed Bid, Uniform Price	2009 2012	30,887,620 2,172,540	30,887,620 2,172,540	$3.23 $2.06
V:9/9/2009	Sealed Bid, Uniform Price	2009 2012	28,408,945 2,172,540	28,408,945 2,172,540	$2.19 $1.87
VI: 12/2/2009		2009 2012	28,591,698 2,172,540		

Source: http://www.rggi.org/co2-auctions/results

Table 3.8: Cumulative Results of RGGI Auctions By State

State	2009 Allowances Auctioned to Date	2012 Allowances Auctioned to Date	Total Proceeds All Auctions
Connecticut	7,237,648	360,957	22,770,582.60
Delaware	3,047,505	200,094	9,841,870.12
Maine	4,230,870	190,365	13,507,410.05
Maryland	26,658,909	1,199,652	84,793,994.54
Massachusetts	21,897,670	985,695	69,650,856.62
New Hampshire	4,758,441	260,550	15,250,315.61
New Jersey	15,277,369	849,894	51,526,159.70
New York	46,568,020	2,329,155	155,299,078.17
Rhode Island	2,193,873	98,724	6,978,050.89
Vermont	1,011,310	45,507	3,216,669.18
Total	134,881,615	6,520,593	432,834,987.48

Source: http://www.rggi.org/co2-auctions/results

As further GHG legislation comes into force, transportation will have to fit into this process as one of the elements contributing to GHG and global warming

3.7 Hours of Service Rules

In 1993 hours of service (HOS) regulations were introduced for truck drivers. Reform of the rules was under consideration by the Federal Motor Carrier Safety Administration (FMCSA) for many years. In 1995 Congress, after studying the effect of fatigue as a contributing factor to motor vehicle crashes, directed FMCSA to begin a new rulemaking to increase driver alertness and reduce fatigue related incidents (FMCSA). In April 2003 the FMCSA issued the first significant revisions to the rules. These were, however, struck down by the D.C. Appeals court. Congress reinstated the rule later that year (FMCSA, 374 F.3d 1209 D.C. Cir. 2004). In 2005 further new rules were introduced regarding the hours that truckers could drive. Table 3.9 compares the new rule with the old 2003 rules. Under this new rule a driver may drive a maximum of 11 hours after 10 consecutive hours off. The driver can restart a 7/8 consecutive day after taking 34 or more consecutive hours of duty.

Table 3.9: Hours of Service Rules

Requirement	Old Rule	New Rule
Off-duty time	8 hours	10 hours
Drive time allowance	10 hours	11 hours
Cycle clock restart after	24 hours	34 hours
On-duty work day	15 hours	14 hours
Extension of work day	Every day	Once/cycle*
* one cycle = 7/8 days		

Source: FMCSA

However, after the issuance of the 2005 rules, the Public Citizen and Owner Operator Independent Drivers Association challenged this ruling. They argued that the FMCSA had ignored a study—which they had commissioned—that showed that there was a substantially higher risk of fatigue-related accidents in the extra hours of service allowed by the new rules. The U.S. Court of Appeals of the D.C. Circuit (Owner Operator Independent Drivers Association v. Federal Motor Carrier Safety Administration (D.C. Cir. 2007) overturned two portions of the new HOS rules, and shortened drivers times back the original 10 hours rules and removed the 34 hour restart period. The American Trucking Association supported the 11 hour rules and it asked the Court to stay its decision and keep the current rule in effect. The court found that the agency did not provide any opportunity for notice and comment on its new model, nor did it explain the methodology or assumptions that underlay the new rules.

FMCSA issued an Interim Final Rule in December 2007 to cover HOS. This continues to limit truckers to 11 hours within a 14-day period, after which they must go off duty for at least 10 hours.

3.8 Idling Reduction

Another area where states have begun to regulate is in heavy duty vehicle idling. Multiple states have introduced idling reduction rules and policies with fines imposed for non-compliance. Maximum idling times run from 3 minutes up to 15 minutes. This has led to many groups using

Alternative Power Units to run engines when drivers are stopped at rest areas or in cities/counties that have introduced idling rules. In 2009 Florida, Maryland, Missouri, North Carolina, New York, Pennsylvania, South Carolina, and Texas all amended their idling regulations (ATRI, 2009).

3.9 Summary

This chapter covered a wide range of U.S. legislation that changed the transportation sector environment over the past decade. Far reaching programs were implemented to make diesel fuel and engines cleaner, and it was implemented over a period that saw trucking demand exhibit “boom and bust” as well as face high fuel prices for over a 15 month period around 2007. Fuel and environmental costs stimulated a variety of operational, vehicle design and changes in consumer choice towards more efficient vehicles. It was the time when hybrids, in various designs, became an accepted and growing representative class, signaling that further Vcost estimation lies ahead.

In all previous studies, representative vehicles have been chosen to allow modelers to develop Vcost data for what might be termed the “average vehicle” in each class. This approach was also adopted for this study using the latest available date from the TxDOT Vehicles Titles and Registration Division, which on November 2, 2009 became the Texas Department of Motor Vehicles, a new state agency. The next chapter describes the work completed to select the representative vehicles for the Vcost study.

Chapter 4. Representative Vehicle Types

4.1 Overview of Representative Vehicles and Fleets

Over 15 million vehicles are registered in Texas, with substantial growth in numbers predicted over the next two decades. These vehicles vary in size, weight, type, engine size, and fuel type. From this population, the study team had to interview TxDOT VTR staff, retrieve substantial quantities of data, and undertake a thorough analysis to determine the representative types to be used in the study. The light-duty representative vehicles finally chosen for inclusion in the Vcost model can be seen in Table 4.1 and the representative fleet distribution can be seen in Table 4.2.

Table 4.1: Representative Vehicle Fleet Utilized in the Vcost Model

CARS AND LIGHT-DUTY TRUCKS			
CLASS CARS (Sedans & station wagons)	VEHICLES CHOSEN AS REPRESENTATIVE		
Subcompact			
Compact	Ford Focus	Honda Civic	Toyota Corolla
Mid-Size	Honda Accord	Nissan Altima	Toyota Camry
Large	Chevrolet Impala	Ford Taurus	Hyundai Sonata
Pick-up Trucks			
Small	Toyota Tacoma	Ford Ranger	Chevrolet Colorado
Standard	Dodge Ram 1500	Ford F100	Chevrolet Silverado 1500
Minivans	< 2% of Texas Fleet		
Vans	< 2% of Texas Fleet		
SUVs and Crossovers			
Small	Ford Escape	Jeep Liberty	Honda CRV
Mid-size	Jeep Grand Cherokee	Ford Explorer	Chevy TrailBlazer
Large	Chevrolet Tahoe	Ford Expedition	GMC Yukon

Table 4.2: Fleet Composition Utilized in the Vcost Model

88% LDVs	59% Cars (Sedans, Station Wagons, Coupes)	27% Compact
		38% Midsize
		35% Large
	27% Pickup Trucks	23% Compact
		77% Large
	14% Sports-Utility Vehicles (SUVs)	37% Compact
		43% Midsize
		20% Large
12% HDVs	65% Class 9 (5-axle tractor-trailers)	
	27% Class 5 (2-axle, 6-tire trucks)	
	8% Class 6 (3-axle, single-unit trucks)	

4.2 Methodology for Determining Representative Vehicles

The methodology for determining the representative vehicles comprised three main tasks shown in Figure 4.1.

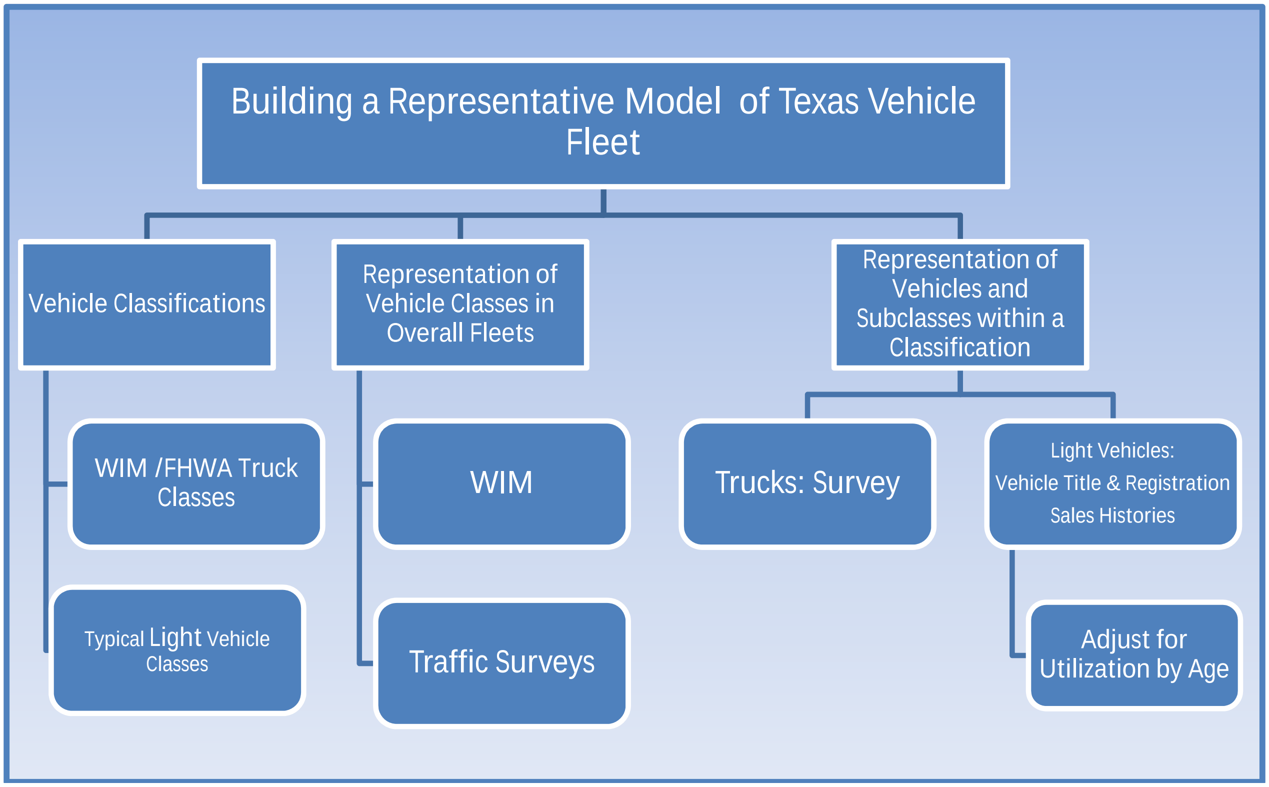


Figure 4.1: Building a Representative Model of Texas Vehicle Fleet

Vcost calculations needed to be estimated for the main classes of vehicles using the TxDOT highway network. A variety of methods, all relatively similar to each other, were used for classifying highway users in surveys. These are briefly described and illustrated. The main classifications that the research team reviewed were the Texas 6, FHWA fleet classifications, and the EPA's classes and LVD/LDT-HDT designations. Table 4.3 shows the Texas 6 Classification scheme and Table 4.4 shows the FHWA Classification Scheme.

Table 4.3: Texas 6 Classification Scheme

Classification Code	Vehicle Type	Link to Figure
1	Motorcycles, passenger vehicles, and small or short-wheel-based pickups	Figure 1-1
2	2 axles, 4-tire single-unit trucks (full-sized pickup trucks)	Figure 1-2
3	Buses (2 and 3 axles)	Figure 1-3
4	2-D, 6-tire single-unit vehicles (includes handicapped-equipped and mini school buses)	Figure 1-4
5	3 axles, single-unit vehicles	Figure 1-5
6	4 or more axles, single-unit vehicles	Figure 1-6
7	3 axles, single trailer (2S1)	Figure 1-7
8	4 axles, single trailer (2S2 or 3S1)	Figure 1-8
9	5 axles, single trailer (3S2, 3S2 split, or 2S3)	Figure 1-9
10	6 or more axles, single trailer (3S3, 3S4, etc.)	Figure 1-10
11	5 or less axles, multi-trailers (2S1-2)	Figure 1-11
12	6 axles, multi-trailers (2S2-2 or 3S1-2)	Figure 1-12
13	7 or more axles, trailers (3S2-2)	Figure 1-13
14	Unclassified (AVC and WIM)	None

Source: TxDOT

Table 4.4: FHWA Classification Scheme

Classification Number	Vehicle Type	Link to Figure
1	Motorcycles	Figure 1 14
2	Passenger cars (with 1- or 2-axle trailers)	Figure 1-15
3	2 axles, 4-tire single-unit pickup or van (with 1- or 2-axle trailers)	Figure 1-16
4	Buses	Figure 1-17
5	2D - 2 axles, 6-tire single unit (includes handicapped bus and mini school buses)	Figure 1-18
6	3 axles, single unit	Figure 1-19
7	4 or more axles, single unit	Figure 1-20
8	3 to 4 axles, single trailer	Figure 1-21
9	5 axles, single trailer	Figure 1-22
10	6 or more axles, single trailer	Figure 1-23
11	5 or less axles, multi-trailers	Figure 1-24
12	6 axles, multi-trailers	Figure 1-25
13	7 or more axles, multi-trailers	Figure 1-26

Source: FHWA

The Texas 6 and FHWA classification schemes are based on truck configuration (axles and trailers) and have 13 classes. The EPA scheme is based solely on weight and has eight classes.

There are a few subtle differences between the Texas 6 and FHWA classifications. The Texas 6 classification lists motorcycles and passenger vehicles in the same category, while the FHWA scheme lists them as separate classes. The Texas 6 classification breaks 3- and 4-axle single trailer vehicles into separate categories, while they are combined as one category by the FHWA classification. Other than these two changes, and the number of the class (if below 9), the classifications are identical. The most common heavy truck (the five-axle, single-trailer vehicle) is Class 9 in both the Texas 6 and FHWA classifications and Class 8 in the EPA classifications. Appendix [ ] has a figure that compares Texas 6 and FHWA classification schemes.

TxDOT uses the FHWA classification system, but it should be noted that the research team did not estimate Vcosts for motorbikes.

4.2.2 Overview of Vcost Classes

A comprehensive set of vehicle classes was necessary for construction of an accurate, sensitive Vcost model.

Vehicle classes fall into two major categories: Heavy-Duty Vehicles (HDVs) and Light-Duty Vehicles (LDVs). Heavy-duty vehicles are defined as trucks according to the Federal Highway Administration (FHWA) definition of vehicle classes. HDVs are in Category 4 or greater. These HDVs are typically commercial vehicles, used for purposes such as freight hauling.

Light-Duty Vehicles are vehicles such as sedans, sports-utility vehicles (SUVs), and normal-sized pickup trucks used primarily for personal transportation (although they have commercial uses such as rental car fleets.) For a full listing of the vehicle classes and representative vehicles, see Appendices B, C, and D.

The basic tables in our analysis capture three to four light vehicle classes (autos and smaller pickups) and three heavy truck classes for the basic cost model. However, the variety of fuel models we developed for light vehicles will permit a more highly disaggregated fuel consumption to be determined—such as scenarios of hybrid vehicle use in future years.

In addition, for the heavy vehicle classes, it will be possible to alter parameters such as weight, engine power, and number of axles to address other vehicle classes or completely new classes such as long combination vehicles.

To get our class break down, our research team reviewed multiple data sources; the following three sources, however, formed the backbone of the fleet distribution and choice of representative vehicles.

- VTR Data
- Weigh-in-Motion Data & Vehicle Counts from TxDOT
- Automotive News Sales History for years 2002 through 2008

The vehicle count data from TxDOT provided a percentage of trucks by category as well as the percentage of light vehicles. The VTR data broke down the light vehicles into common class types (sedans, trucks, SUVs, and vans) in order to, among other things, weight the relative roadshare of each class, and to determine the typical weight break-down for light-duty vehicles. Weight-in-motion data helped to define the heavy-duty vehicle classes.

Light-Duty Vehicles Classification Scheme

The U.S. DOT light-duty vehicle categorization (which can be found in Appendix B) was taken as a starting point, and then modified such that it reflected sensitivity to the vehicles that were encountered in the Texas-wide fleet. For example, instead of separate categories for sedans, two-door vehicles, station wagons, and hatchbacks, these vehicles were all combined into a “car” class because research showed that sedans comprised the vast majority of that class, and that price differentials between these body types were negligible. Analysis of VTR data (provided in detail in Chapter 3) showed that vans and minivans comprised merely 2% of the vehicle fleet, less than even any subclass of a major LDV class. For this reason, vans were removed as a major vehicle class in the representative vehicle sample. Also, mini-compact and subcompact LDVs were absorbed into the “compact” car category as they comprised less than 5% of the compact car subclass. The resulting classification scheme consists of three main classes, each with two to three sub-classes as can be seen in Table 4.5.

Table 4.5: LDV Classification Scheme

Cars	Pickup Trucks	SUVs
Compact	Compact	Compact
Midsize	Large	Midsize
Large		Large

Heavy-Duty Vehicles

For HDVs, analysis of TxDOT’s Weigh-in-Motion (WIM) data and Vehicle Count (VC) data was used to determine the relevant categories of heavy trucks on Texas roads. Texas registration data was not used because a significant portion of 5-axle tractor-trailer (FHWA Class 9)[13] truck traffic is registered in other states, and FHWA Class 9 trucks registered in Texas may spend a considerable portion of their operation in other states.

The FHWA classification scheme lists 13 separate vehicle categories, 10 of which are for HDVs. To determine which of the categories constituted a statistically meaningful segment of Texas road traffic, TxDOT vehicle count data was analyzed. The 2006 TxDOT vehicle count data set used in this research was aggregated from 88 different stations across Texas, and listed the vehicle counts by FHWA class. From this, the ratio of HDV traffic to LDV traffic could be determined (HDVs were 12% of traffic, on average.) The traffic for each class of truck was also compared to determine which vehicle classes were significant. This is shown in Figure 4.2.

[13] When referring to trucks by class designation, the FHWA scheme is used, rather than the EPA or other classification scheme. A comparison of truck classification schemes is listed in Appendices B and C.

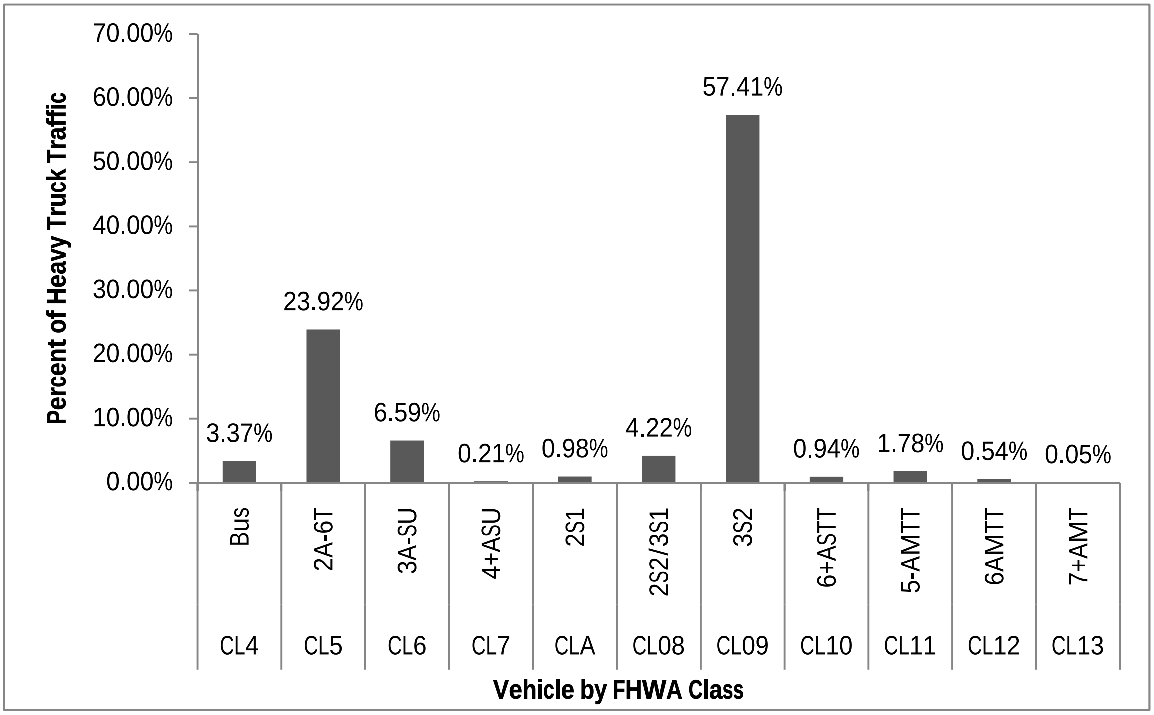


Figure 4.2: Percentage traffic for each truck class

All HDVs constituting 5% or more of the overall HDV traffic were chosen to be significant. This resulted in FHWA Classes 5, 6, and 9 being chosen as representative classes. The Class 9 truck (referred to as a "Class 8" by those using the EPA scheme) constitutes the majority of HDV traffic in Texas.

4.3 Representative Vehicles

To find the operating cost for a particular vehicle class, several vehicles belonging to that class were chosen to be representative vehicles. The operational costs for these vehicles were then calculated and averaged to provide the overall operational cost for this class. Thus, it is important that these representative vehicles are chosen such that they represent, as accurately as possible, the vehicles comprising their class.

4.3.1 Light-Duty Vehicles

In addition to the VTR data set, a vehicles sales data set was also used to develop the representative vehicle set and flesh-out the fleet composition. A dataset giving U.S. vehicle sales by nameplate from Automotive News was analyzed for multiple calendar years (2002, 2003, 2004, 2005, 2007, and 2008). The results were differentiated by vehicle class, and a table of sales by vehicle class and subclass was generated. In each category, sales were also differentiated by model and make. The sales for several different years were thus analyzed to see which models and makes dominated the sales in each vehicle subclass. It was found that generally between three and five models represented the majority of sales in that subclass; and that three models represented, at the least, 30% of all sales in that subclass. For each subclass, three models were chosen as the representative vehicles for that class. The results of this analysis are displayed in Figure 4.1 and in Appendix E.

4.3.2 Heavy-Duty Vehicles

Concerning the HDVs, while the vehicle count data specified the axle-trailer arrangement of the vehicles in question, in order to specify the representative vehicle more information was needed. The most pertinent factor is the weight of the vehicle.

WIM records not only the weights of vehicles passing over the sensor, but also the number of axles, weight per axle, and whether a trailer(s) was towed. A C++ script was written to parse the WIM data entries for each event, extracting all vehicles of a certain axle configuration and recording the weights observed. This was used to generate a weight profile for each of the truck configurations of interest. The output from this analysis can be seen in Figures 4.3 and 4.4 and Tables 4.6 and 4.7. Notice this weight is the typical loaded weight of the vehicle- not the curb weight or the gross vehicle weight rating. These weight profiles, along with the axle-trailer designation from the FHWA class designation, allow specification of the class and representative vehicle. The Weigh-in-Motion and vehicle count analysis for HDVs can be seen in Appendix F.

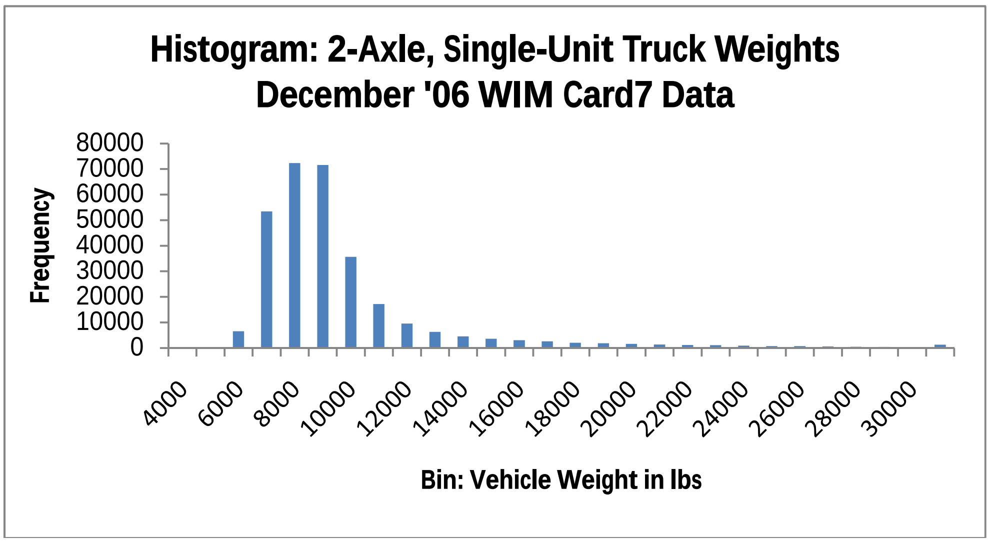


Figure 4.3: WIM Data—2 Axle, Six-Tire Truck Weights(Class 5)

Table 4.6: Statistical Analysis of WIM Data 2 Axle Units

2ASU	Vehicle Weight (lb)
Median	8300
Average	9277
St Dev	3832
Min	4700
Max	74900

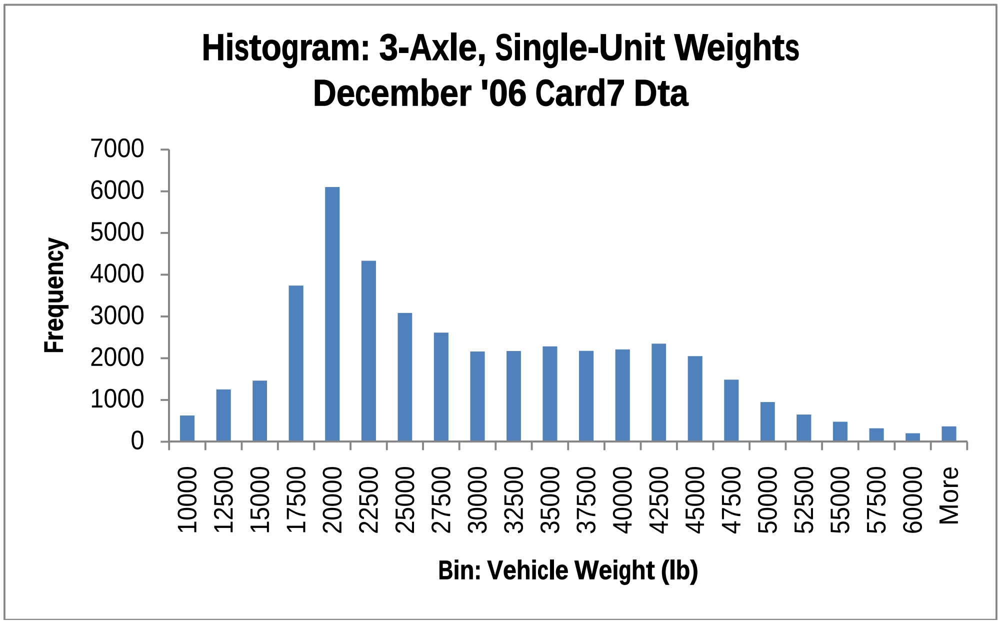


Figure 4.4: WIM Data—3 Axle Single-Unit Truck Weights (Class 6)

Table 4.7: Statistical Analysis of WIM Data 3 Axle Units

3ASU	Vehicle Weight (lb)
Median	35000
Average	35000
St dev	15512
Max	60000
Min	10000

Only the first HDV class, the FHWA Class 9 5-axle tractor-trailer (EPA Class 8) is currently under implementation in the fuel model. The HDV section of the model will be updated when advanced fuel data and other resources are developed in the extension to this research project. The 5-axle tractor-trailer class has two representative vehicles. One represents an owner-operated vehicle, the other a typical company fleet vehicle. Information to describe the fuel use and other properties of these vehicles was found from sources including literature, industry publications, and surveys.

4.4 Fleet Composition

One of the strengths of this model is that it does not just provide operational costs for various vehicles, but also calculates the average per-vehicle cost for a user-defined fleet.

The fleet composition in the model is defined by the percentages of each of its constitutive vehicle classes and subclasses. For example, a fleet may be defined as a percentage of heavy trucks and light-duty vehicles. The light vehicles may then comprise, for example, another set of percentages (cars, pickups, and SUVs.) This sub-category can also be broken-down or be sub-categorized into three further classes (e.g., compact cars, mid-size cars, and large cars).

In many cases the fleet composition will be set by the user, often working from resources such as vehicle-count surveys. However, the user may not have access to the necessary resources and yet will want to make general estimates based on Texas traffic. For this reason, it was considered important to provide a rigorously researched default case, representing Texas vehicular traffic in aggregate.

This functionality was also created and developed to allow the user to be able to tailor the model to the different fleet compositions and produce different output to guide policy makers and financial decision makers within TxDOT, the MPOs, and the RMAs. As an example, the model could be very useful in understanding the effects of the recent "Cash for Clunkers" program on fuel efficiency costs and potential gas tax revenues.

4.4.1 Default Texas Fleet Composition

Several sources were used to determine the Texas fleet composition, including Texas WIM data, traffic (vehicle count) surveys, and VTR data.

Traffic surveys record the number of vehicles passing by a certain area and categorize them by vehicle type. The research team analyzed the 2006 vehicle count data for 84 locations across Texas. General statistical traits emerged. For instance, the percentage of heavy truck traffic compared to overall traffic was in the range of approximately 12%. The traffic survey data also allowed the research team to set the default range for the percent composition of the heavy-duty truck categories in the model.

The VTR data, pulled from TxDOT's database in August 2008, provided a list of current vehicle registrations that could be differentiated by parameters such as body type, model year, and vehicle weight.

Information on individual vehicles, vehicle model names, VINs, EPA vehicle class, and cargo capacity was not available from this dataset. This was problematic, as we desired to examine registrations by vehicle class and model year. The U.S. DOT classifies sedans by cargo space (in cubic feet), a value not available to us in the VTR data pulls.

To work around these limitations, automobile information from www.Intellichoice.com was used to estimate and map out vehicle weight and class. For all current vehicle models, the weight and vehicle classifications were assembled in an Excel spreadsheet. For each EPA vehicle class, a weight distribution histogram was created. The weight histograms were compared across each vehicle class and ranges of weights for each vehicle class were generated. This gave us a weight range for compact, midsize, and large sedans and SUVs, which were used in the official database query to VTR (which can be seen in Appendix A).

Data was retrieved from the VTR in terms of vehicle registrations per model year for each of the specified vehicle classes. In addition, registrations by make and model year was also provided for the major class categories (cars, SUVs, pickups). This information is presented in Appendix D.

In the VTR database results, only a small percentage of total SUVs and pickups were classified by weight. For this reason, VTR data could not be used to fix the percentage composition of pickup and SUV subclasses. National data from vehicle sales histories was used instead to develop these percentages.

Next, the data had to be weighted by road share (or VMT times registrations) to accurately capture operating costs. Older vehicles are driven less than newer vehicles and the data needed to be calibrated to capture this element. While the VTR information represented vehicle registrations in Texas, it did not necessarily represent road share. Therefore, to find a relation between yearly utilization and vehicle age, the table numbered 4.5 from the Transportation Energy Data Book [U.S. DOE, 2009] was used (to develop an equation to approximate utilization. A polynomial curve fit was made to the data, which gave an expression for yearly utilization as a function of age. This can be seen in Figure 4.5.

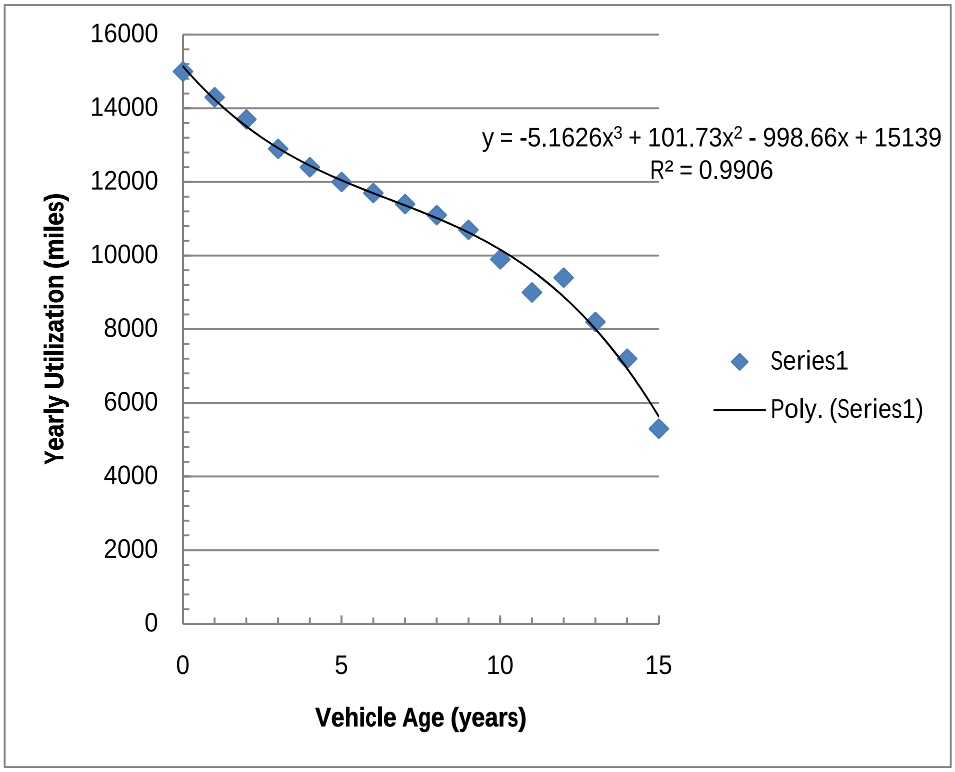


Figure 4.5: Vehicle Utilization as a Function of Age

To get the road share of a vehicle class of a particular model year, the number of registrations was multiplied by the utilization associated with that age of vehicle. This gave a value in vehicle-miles travelled (VMT). The resulting classification scheme after this calibration took place can be seen in Table 4.8.

Table 4.8: Vehicle Classification Scheme Used in the Vcost Model

88% LDVs	59% Cars (Sedans, Station Wagons, Coupes)	27% Compact
		38% Midsize
		35% Large
	27% Pickup Trucks	23% Compact
		77% Large
	14% Sports-Utility Vehicles (SUVs)	37% Compact
		43% Midsize
		20% Large
12% HDVs	65% Class 9 (5-axle tractor-trailers)	
	27% Class 5 (2-axle, 6-tire trucks)	
	8% Class 6 (3-axle, single-unit trucks)	

4.5 VTR Data

The information from the VTR data set assisted in forming the class structure and fleet composition for the Vcost model.

Data was taken on vehicles registered in Texas as of August 2008. Details on the specifications of the data pulls can be found in the VTR Query document attached as Appendix A to this Technical Memorandum. The two basic categories examined were passenger cars and passenger trucks. The passenger truck category was further divided into pickups, SUVs, and vans.

Weight was used to separate approximate vehicle sub classes (for example, passenger cars into compact, mid-size, and large sedans). Because the VTR database could not provide model name or interior space, the exact EPA classification could not be determined (for passenger cars, EPA uses interior space in cubic feet). Using data provided by the consumer car sales guide Intellichoice.com, the 2008 vehicle fleet was analyzed to correlate vehicle weight to EPA category and set rough weight limits to define the subclasses used for VTR.

4.5.1 Passenger Cars Age Distribution in Texas

To understand the distribution of vehicle ages, both percent registration and percent road share were plotted by model year (Figure 4.6). Recall that road share is the number of registrations of a particular model year times the average utilization (VMT) of vehicles of that age.

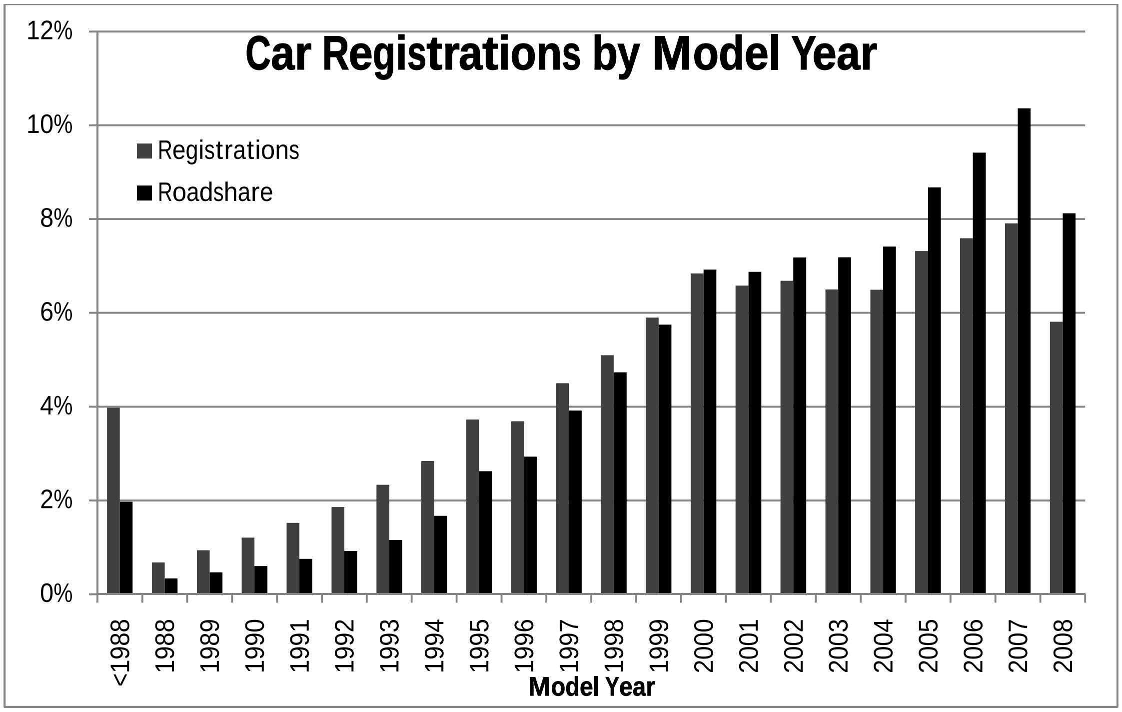


Figure 4.6: Car registrations by model year, 1988–August 2008

As could be expected, newer cars are more commonly driven. Over 96% of the cars were from model years 1988 and above. In addition, the older a car is, the lower the yearly utilization, so cars over 20 years have even more minimal impact on the overall driving fleet. (Data supporting this was found from the Transportation Energy Data Book (26th edition), published by the U.S. Department of Energy and Oak Ridge National Laboratory.) For these reasons, from this point on, only vehicles of model year of 1988 or above are considered.

For registered passenger cars of model year 1988 and above, the average model year was 2001. The model years were correlated to vehicle ages by subtracting the model year from 2008 and adding 0.5. For registered passenger cars of model year 1988 and above, the average age of a passenger car was 7.52 years.

The U.S. Department of Transportation estimated the average age of a passenger car as 8 years in the 2001 National Household Travel Survey. A more recent estimate put the median vehicle age at 9.2 years (Transportation Energy Data Book, Table 3-9, 27th Edition). Because this data was (presumably) not cut off at a vehicle age of over 20 years, it is suspected that much older vehicles are skewing the average larger, even though, statistically speaking, they are driven very little. There also may be significant variations in the automotive market comparing Texas to the nation as a whole.

The cumulative distribution of passenger cars with model years 1988 and above was calculated for Texas from VTR data and can be seen in Figure 4.7. VTR data shows that around 95% of registered vehicles are at or below 15 years. About 70% are less than 10 years old.

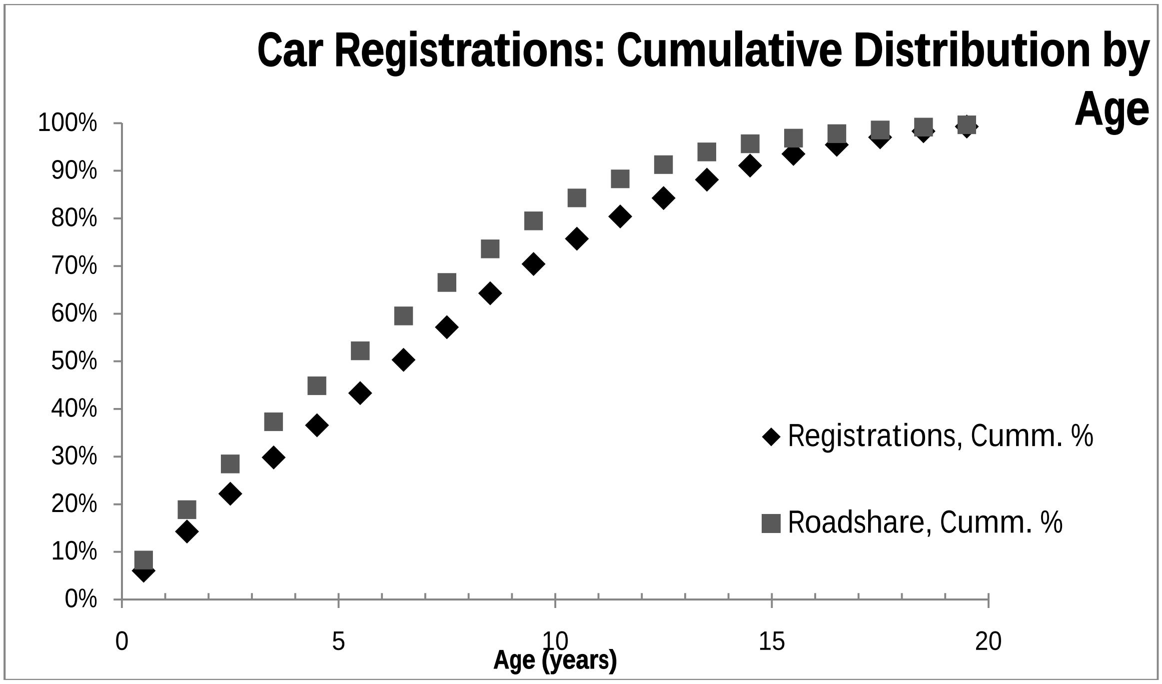


Figure 4.7: Cumulative distribution of car registrations/road share with age

4.5.2 Classes and Body Types in Texas

The VTR database divides passenger cars into body types. The following categories: sedans, station wagons, Sport, and **LL** are the body types associated with cars. The **LL** body type is typically used to refer to SUVs, so it is assumed these vehicles are small crossovers. The VTR Data shows that the vast majority of passenger cars are registered as sedans (Figures 4.8 and 4.9).

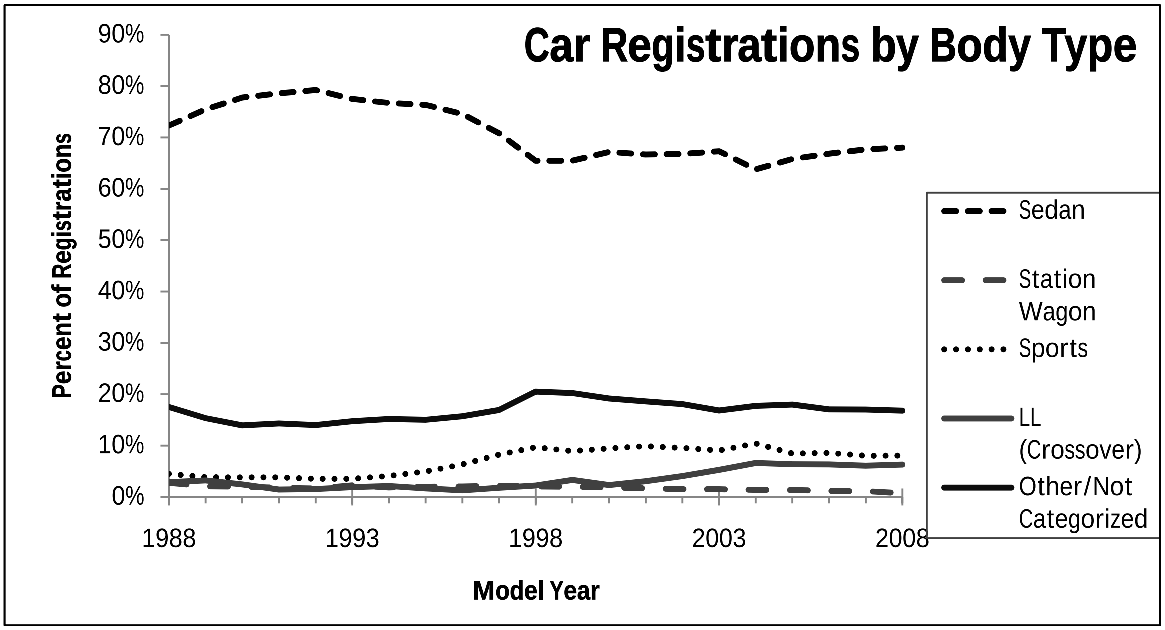


Figure 4.8: Car body style registrations as a percentage of total car registration, by model year, from 1998–August 2008

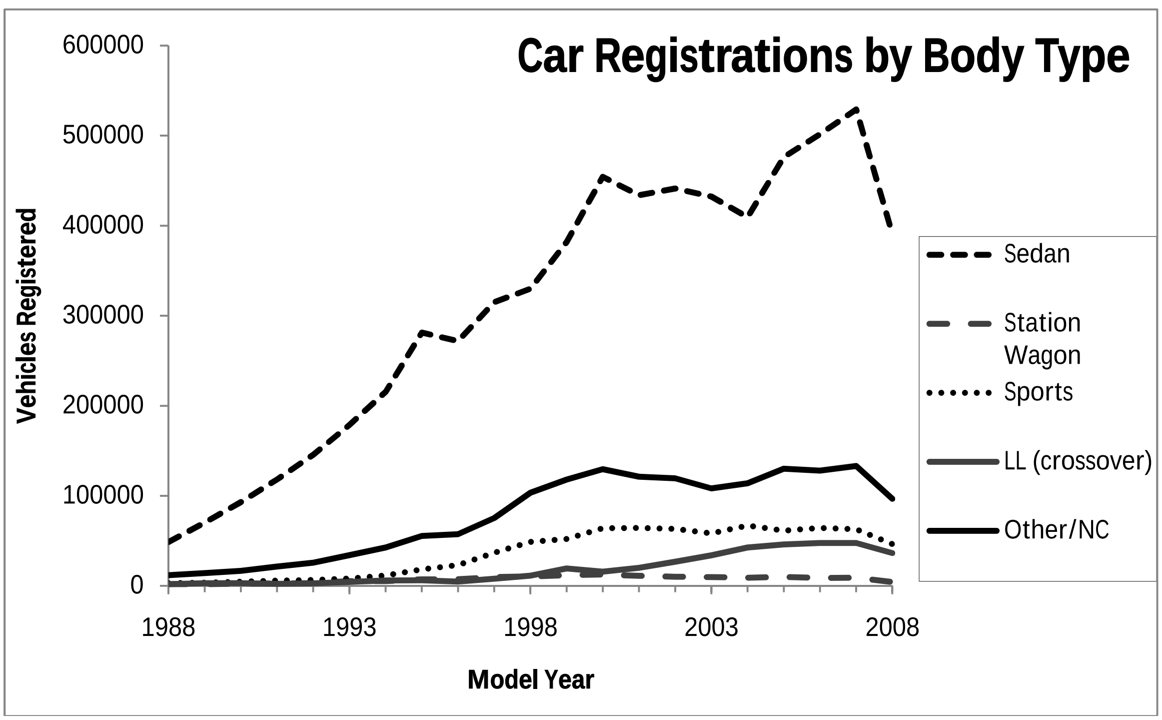


Figure 4.9: Car registrations by body style, by model year, from 1998–August 2008

The subclasses of passenger cars were found for each of these body types. Because the sedan body type dominates, showing the subclass makeup of each body type is not necessary. The subclass for all passenger cars combined is shown in Figure 4.10.

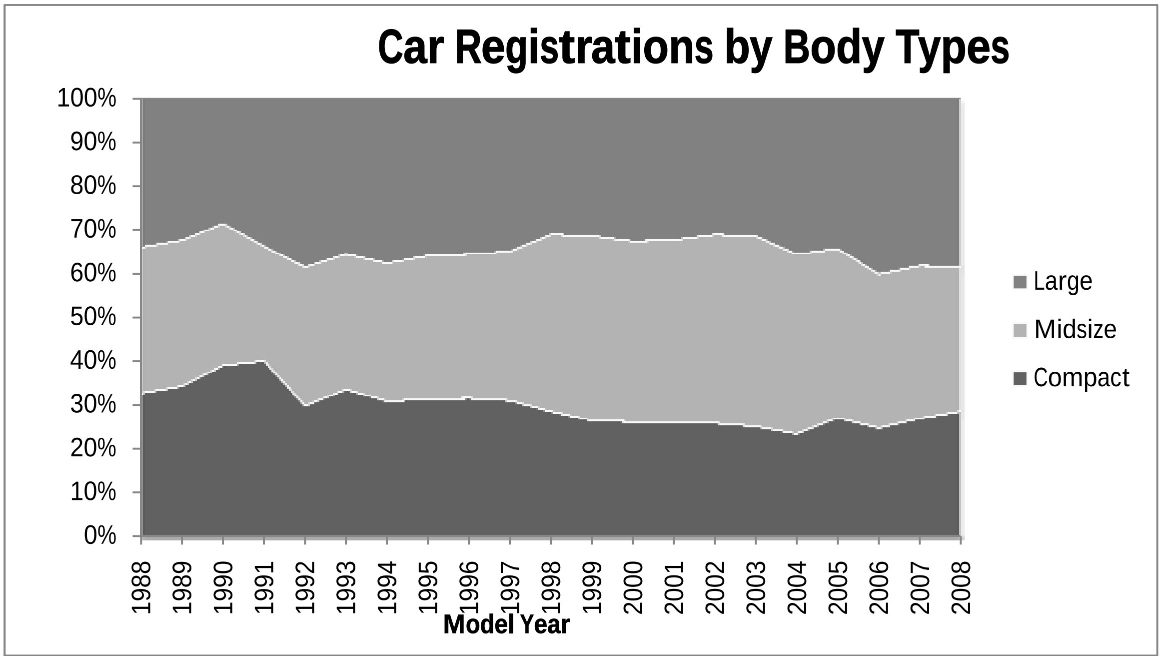


Figure 4.10: Car registrations by subclass, per model year, from 1998–August 2008

4.5.3 Passenger Truck Age Distribution in Texas

The passenger truck category is comprised of pickups, SUVs, and vans. Roughly 65%, 30%, and 5% of trucks are pickups, SUVs, and vans, respectively. The average age of trucks for model year (MY) 1988 plus was 7.15 years. Figures 4.11 and 4.12 show this breakdown.

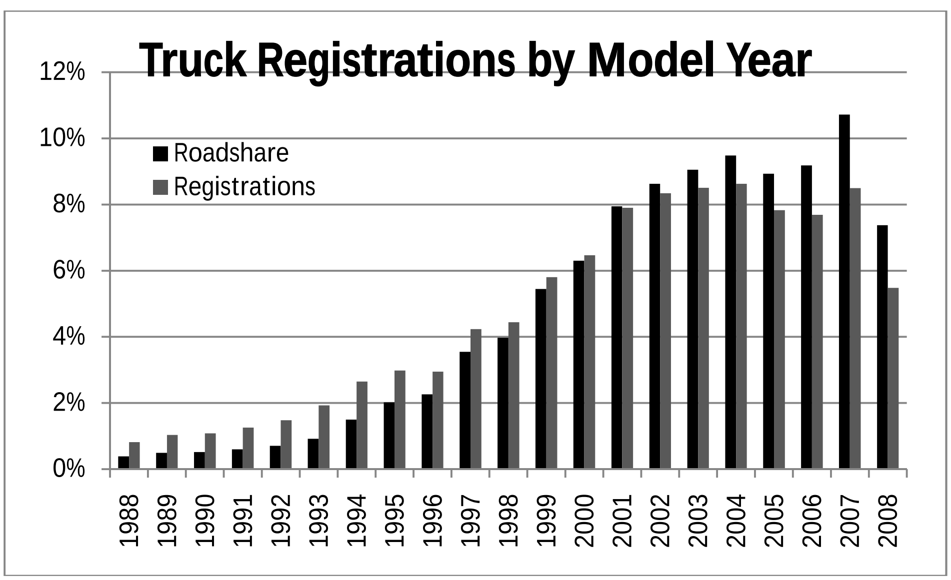


Figure 4.11: Average Age and Road share of Light-Duty Trucks in Texas

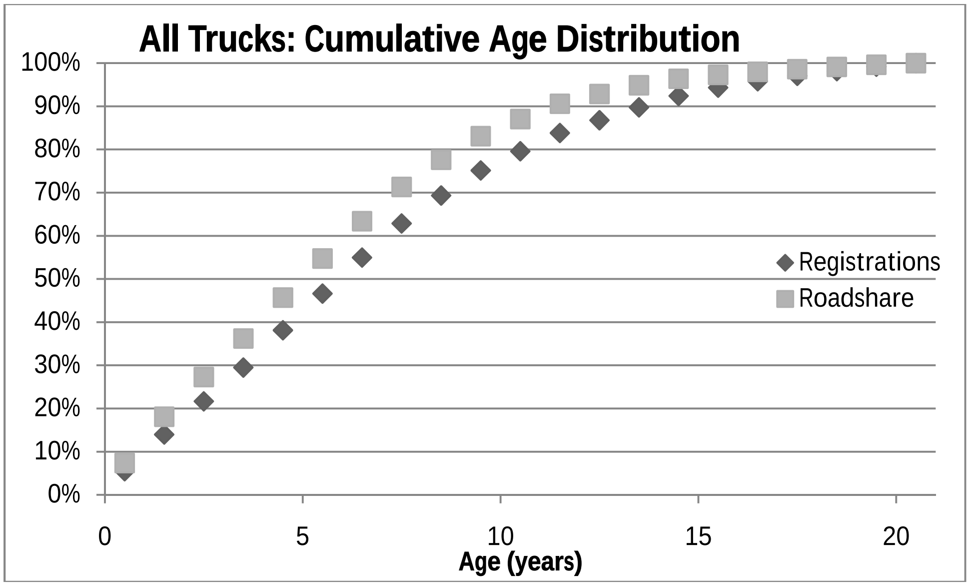


Figure 4.12: Light-Duty Trucks—Vehicle Age Distribution

4.5.4 Pickups Age Distribution in Texas

The average age of pickups for MY 1988 plus was 7.73 years (Figures 4.13 and 4.14).

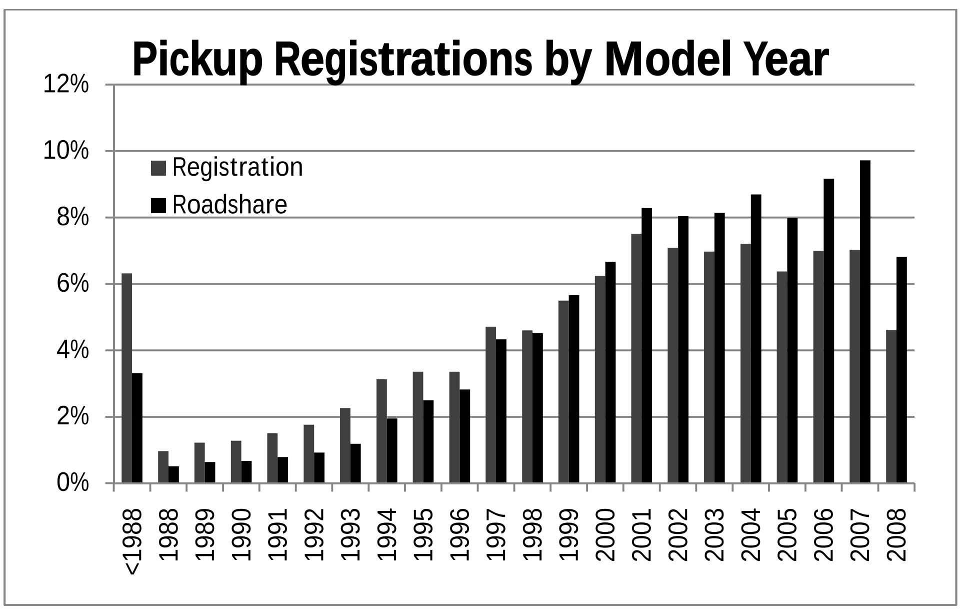


Figure 4.13: Average Age and Road share of Pickups in Texas

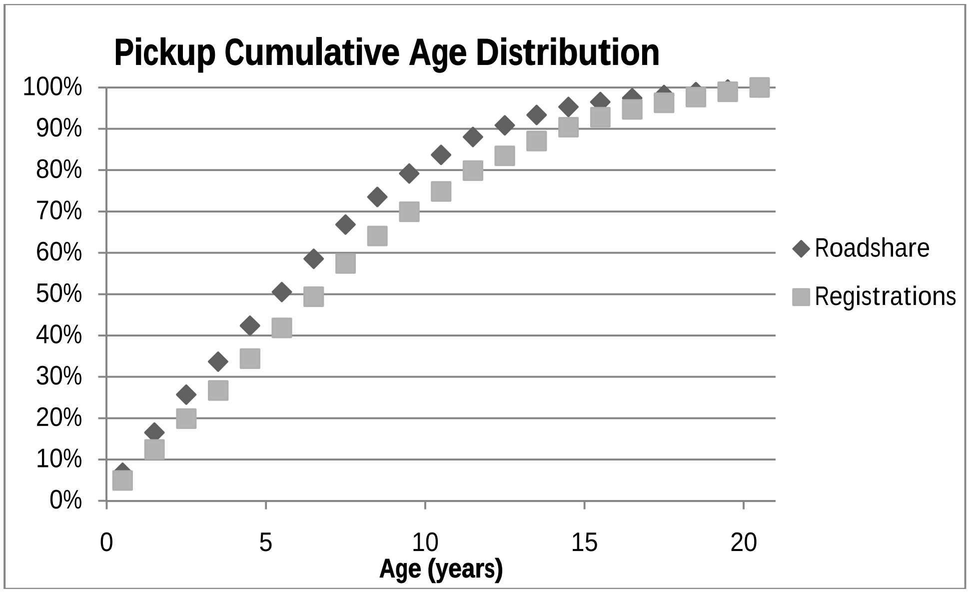


Figure 4.14: Pickups—Vehicle Age Distribution

Pickups are divided into compact and large based on EPA weight specifications (Figure 4.15). For some reason, many of the trucks in the database were not categorized by weight into either compact or large classes. It may be that the weight for these vehicles was unknown. For this reason, the truck subclasses were not determined from VTR data, but from national sales records. The same is true for SUVs.

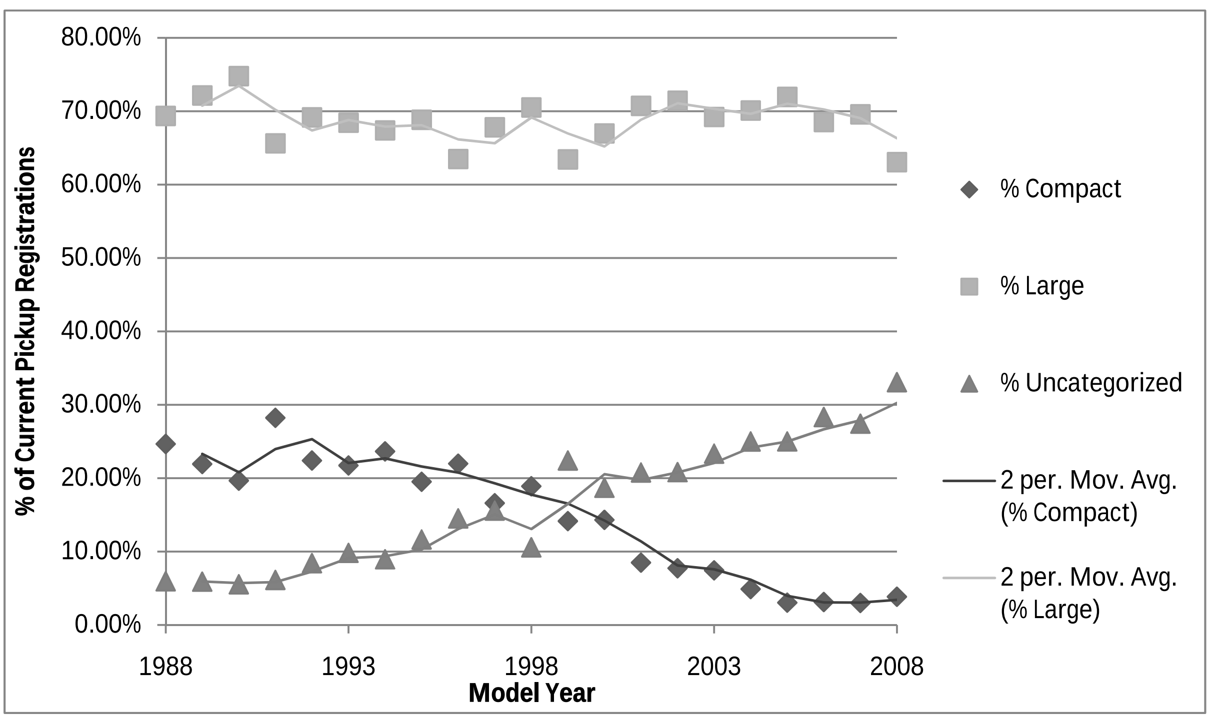


Figure 4.15: Breakout of Pickups

4.5.5 SUV Age Distribution in Texas

It should be noted that SUVs are statistically much younger than light-duty trucks in general. This combined with their relatively low fuel economy and high purchase price (and thus depreciation) results in them costing significantly more to operate. The average age of SUVs for MY 1988 plus was 5.79 years (Figures 4.16 and 4.17).

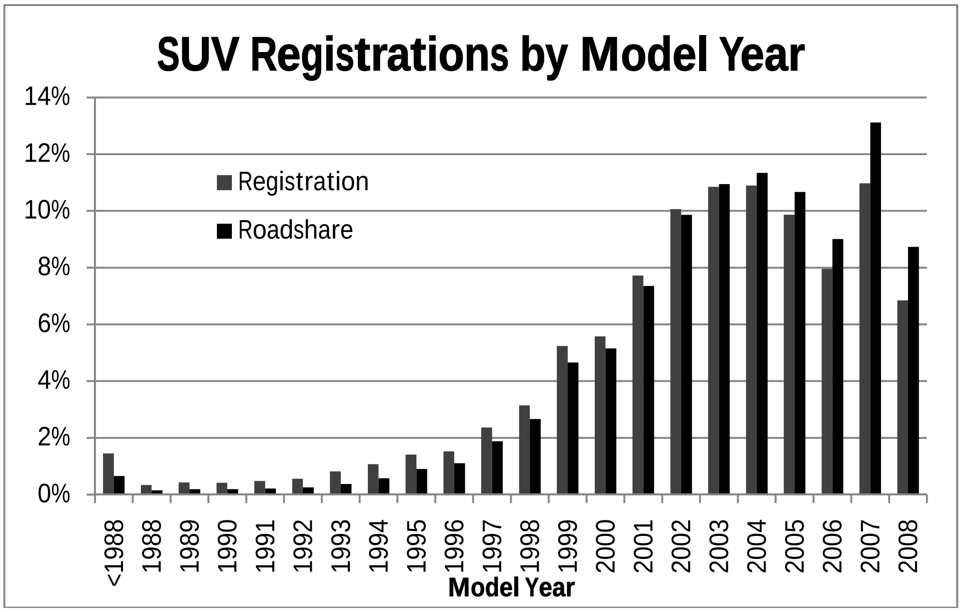


Figure 4.16: SUVs—Age by Model Year

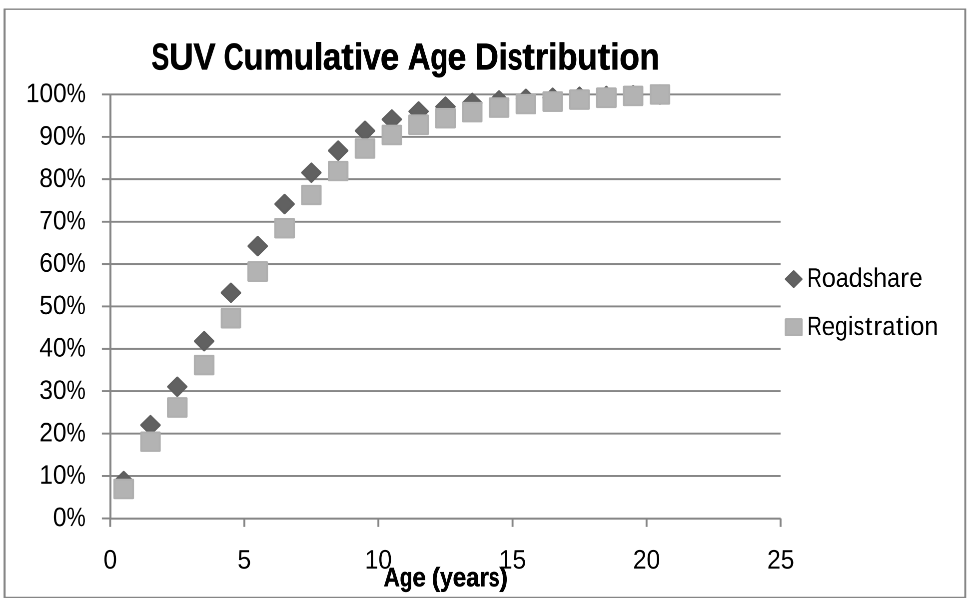


Figure 4.17: SUVs—Vehicle Age Distribution

4.5.6 Van Age Distribution in Texas

Vans comprised only 2% of the total fleet, and are much older, and therefore driven less. Because of this they were not chosen as a major fleet category. Figures 4.18 and 4.19 show the breakdown of van registrations.

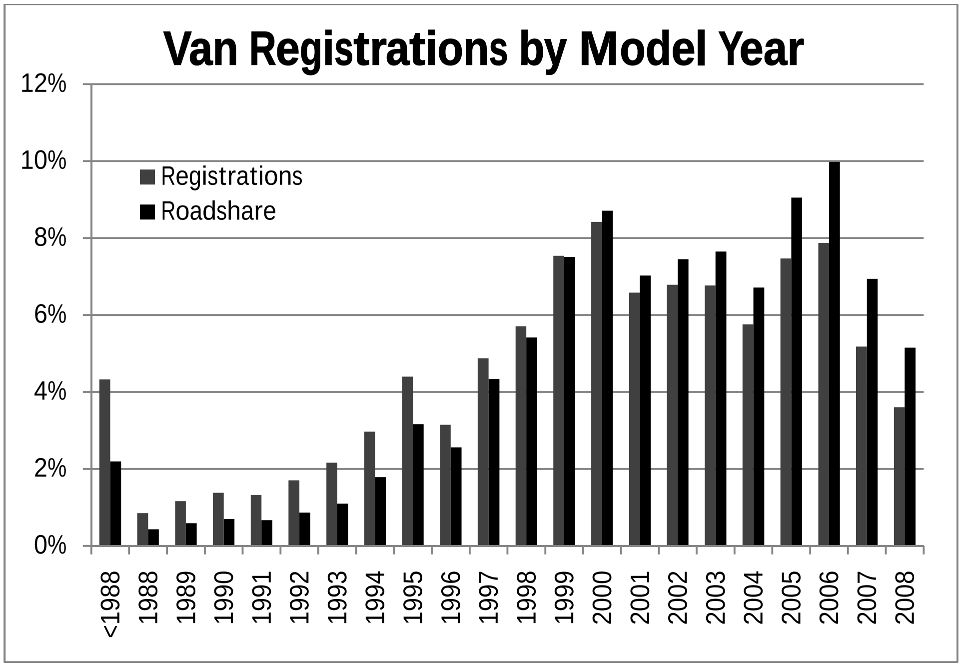


Figure 4.18: Vans—Age by Model Year

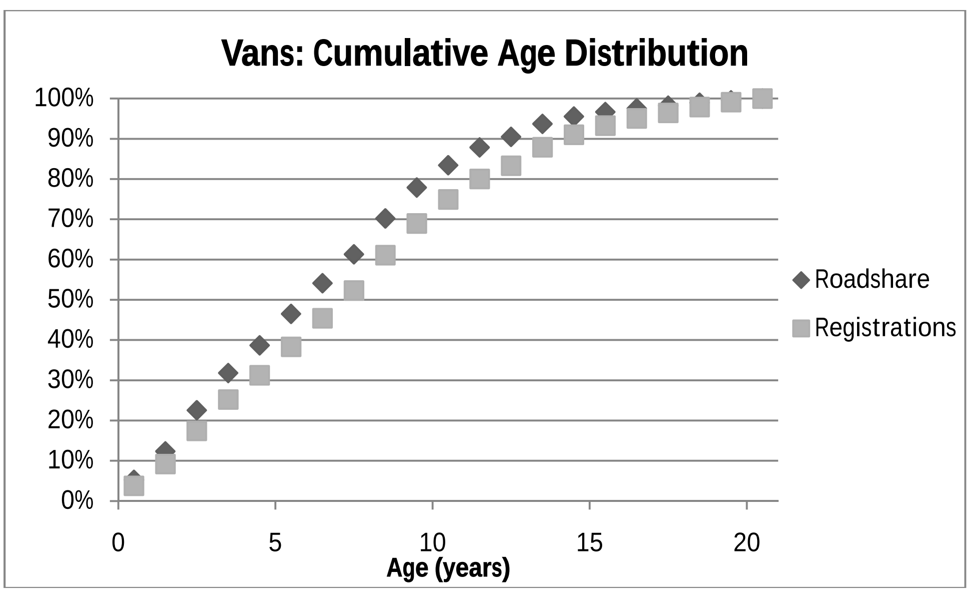


Figure 4.19: Vans—Vehicle Age Distribution

4.5.7 Summary of VTR Data

Looking at recent registration data, overall, cars made up 58% of the registrations and light-duty trucks the remaining 42% (Figure 4.20).

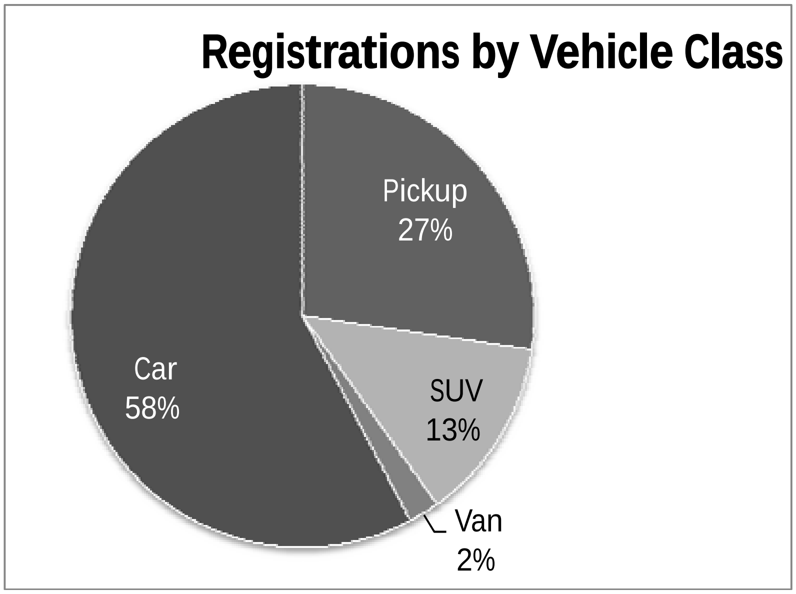


Figure 4.20: Total Registration by Vehicle Type

The ratio of passenger cars to the passenger truck classes varies significantly, depending upon model year (Figure 4.21).

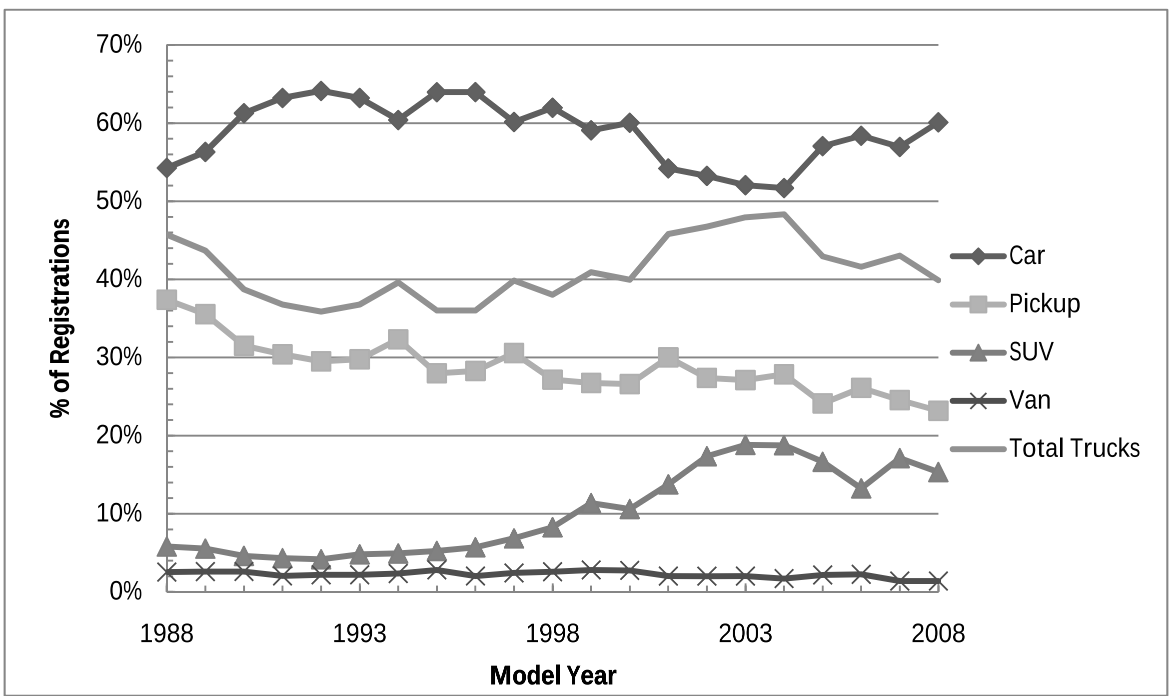


Figure 4.21: Ratio of Passenger Cars to Light-Duty Trucks—by Model Year

4.6 Summary

Extensive analysis of TxDOT VTR data permitted the research team to develop the key representative classes need to mirror the characteristics of the current registered fleet. Numerically light duty vehicles (LDV) dominate the VTR data base and this supports the decision to use a fuel consumption model capable of estimating the consumption of a wide range of LDV models. Heavy duty vehicles comprise only 12% of the registered fleet, of which around 8% are Class 9 trucks of the type seen on the major Texas freight routes. It should be remembered that these vehicles typically operate between 10 to 20 times more vehicle miles of annual travel than the typical metropolitan LDV. In addition, the interstate corridors across the state are also used by Class 9 vehicles registered in other states, so this truck class is an important member of the representative class. The next chapter turns to a critical part of the study, namely estimating fuel consumption for Texas vehicles.

Chapter 5. Modeling Vehicle Fuel Economy

5.1 Introduction

It is obvious from the information in Chapter 3 that developing models for the fuel economy of current vehicles is extremely important because 1) the prior models are a quarter of a century out of date, 2) emissions regulations passed during the last 25 years, together with proposed emissions regulations, especially for heavy-duty vehicles, impacts fuel efficiency, and 3) the increasing price of fuel, together with new CAFÉ standards and consumer demands, has had an impact on fuel efficiency, especially with respect to the introduction of hybrid cars and trucks. Therefore, the fuel economy models discussed in this chapter differ significantly from those available previously.

For the purposes of emissions and fuel economy regulations, the EPA and the U.S. DOT divide on-road vehicles into two categories: light-duty vehicles (LDVs) and heavy-duty vehicles (HDVs). To predict the vehicle performance in both the LDV and HDV classes, application of some fundamental principles of physics is required, as discussed in Section 5.2. The light-duty vehicle fuel economy models developed for this project are discussed in Section 5.3. Section 5.4 provides a discussion of the fuel economy model generated for heavy-duty vehicles. Section 5.5 provides a brief discussion of how the end user will run the "vehicle-specific" fuel economy model.

5.2 Fundamental Model for Vehicle Fuel Economy

The fuel economy (FE) of a vehicle that is operating at steady state (this derivation is also valid when the vehicle is not undergoing rapid changes in speed) in mpg (miles/gallon) is simply the ratio of the vehicle speed, S, in mph (miles/hour) to the volumetric rate of fuel consumption (gallons/hour)

$$FE = \frac{S\rho_f}{\dot{m}_f} \quad FE\left[{}^{miles}\!/\!{}_{gallon}\right] = \frac{S\left[{}^{miles}\!/\!{}_{hour}\right]}{\dot{V}_f\left[{}^{gallons}\!/\!{}_{hour}\right]} \qquad 5.1$$

Multiplication and division of Equation 5.1 by the density of the fuel, ρ_f, yields:

$$FE = \frac{S\rho_f}{\dot{m}_f} \qquad 5.2$$

where is the mass consumption rate of the fuel, a parameter that is useful for developing a physically-based fuel economy model.

Here, it is useful to introduce the definition of a parameter, the brake specific fuel consumption (bsfc), which is routinely used in the engines industry as a measure of fuel efficiency. The bsfc is the mass rate of fuel consumption per unit of power produced by the engine at that specific operating condition (rpm and torque, the combination of which produces this power):

$$bsfc \equiv \frac{\dot{m}_f}{bp} \qquad 5.3a$$

where bp is the "brake power" output (power at the engine output shaft).

Rearranging Equation 5.3a yields:

$$\dot{m}_f = bsfc \cdot bp \qquad 5.3b$$

Here, it should be noted that the bsfc and the engine efficiency are inversely related; because one seeks a high engine efficiency, then one seeks a low bsfc. Specifically, it can be shown (Matthews, 2009) that:

$$\text{bsfc}=\frac{\dot{m}_f}{bp}=\frac{1}{\eta_e LHV_p} \qquad 5.4$$

where η_e is the overall engine efficiency and LHV_p is the "constant pressure Lower Heating Value" of the fuel (the chemical energy density of the fuel).

Substitution of Equation 5.4 into Equation 5.3b yields:

$$\dot{m}_f = \text{bsfc}\cdot bp=\frac{bp}{\eta_e LHV_p} \qquad 5.5$$

Substituting Equation 5.5 into Equation 5.2 yields:

$$FE=\frac{S\rho_f}{\dot{m}_f}=\eta_e\left(\rho_f LHV_p\right)\left[\frac{S}{bp}\right] \qquad 5.6$$

Equation 5.6 quantifies how the fuel economy of a vehicle depends upon 1) the overall efficiency of the engine, 2) two properties of the fuel (the physical density and the chemical energy density), and 3) the ratio of the vehicle speed to the brake power output required from the engine in order for the vehicle to achieve this vehicle speed.

This last term (the term is square brackets in Equation 5.6) requires modification in order to develop a fundamental model for a vehicle's fuel economy. Specifically, the brake power output from the engine must be related to the power required at the tire-road interface. The brake power is reduced through the drivetrain due to inefficiencies in the transmission and differential (the two of which are combined into a single housing in front wheel drive vehicles that have a transaxle). Therefore:

$$p_{mot} = bp\cdot\eta_t\cdot\eta_d \qquad 5.7$$

where η_t is the efficiency of the transmission, η_d is the efficiency of the differential, and p_{mot} is the motive power at the tire-road interface.

Therefore, the term in square brackets in Equation 5.6 becomes:

$$\frac{S}{bp}=\frac{\eta_t\eta_d S}{p_{mot}} \qquad 5.8$$

Substitution of Equation 5.8 into Equation 5.6 yields:

$$FE=\left\{\eta_e\eta_t\eta_d\right\}\left(\rho_f LHV_p\right)\left[\frac{S}{p_{mot}}\right] \qquad 5.9$$

The term in square brackets in Equation 5.9 is the inverse of a force, the motive force that must be applied at the tire-road interface to overcome the forces that are resisting the motion of the vehicle. Figure 5.1 is an illustration of the forces resisting the movement of a vehicle driving on a road at a steady speed.

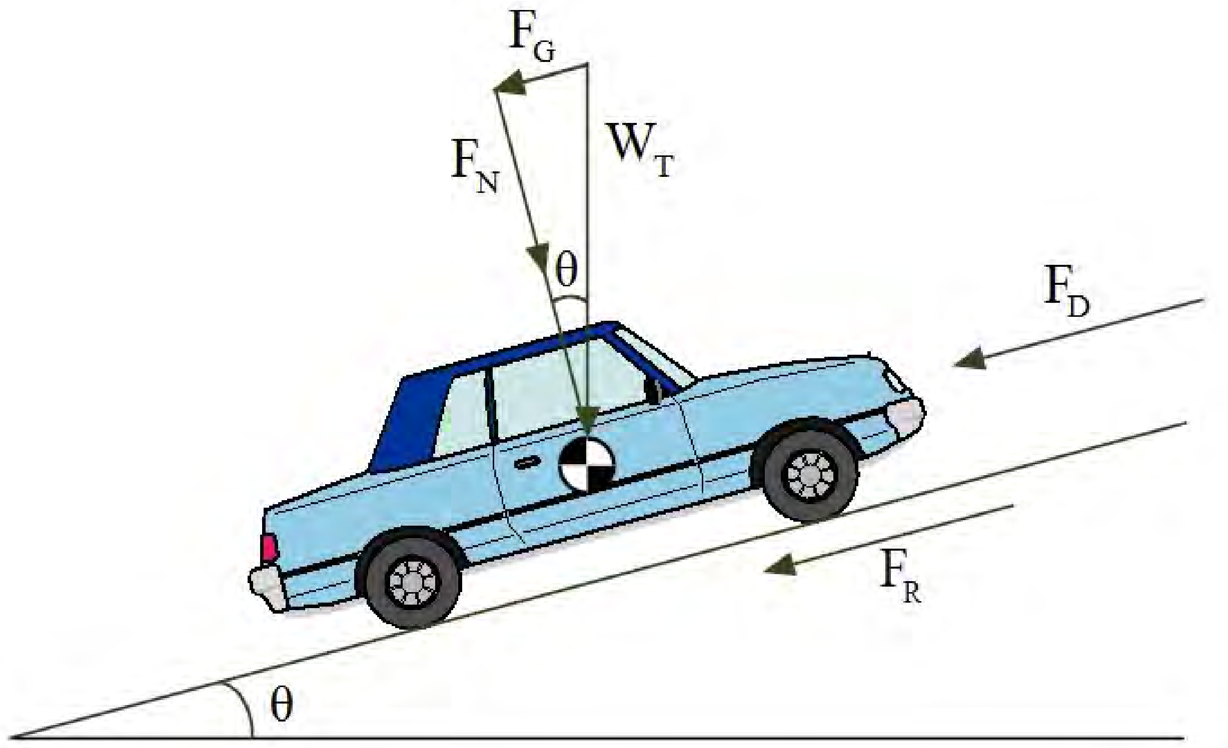


Figure 5.1: Forces acting on a vehicle driving at steady speed.

The total resistive force, F_{res}, is the result of various individual forces that are additive. These forces are the aerodynamic drag force (F_D), the rolling resistance (F_R), and the force imposed by a grade (F_G):

$$F_{res} = F_D + F_R + F_G \qquad 5.10$$

These forces are illustrated in Figure 5.1, which also shows the force imposed by the "loaded" (total) weight of the vehicle (W_T), which acts toward the center of the earth, and the force that is acting normal to the road surface (F_N) for a vehicle that is climbing a grade of angle θ.

The aerodynamic drag force is due to the resistance of the air to the movement of the vehicle. If S is the speed of the vehicle and the wind is blowing at total velocity U, with the component of the wind that is aligned with the direction of vehicle motion given symbol U_x and the component of the wind that is perpendicular to the direction of vehicle motion given symbol U_y, the aerodynamic drag force is:

$$F_D = \frac{1}{2}\rho_{air} C_D A \left(S \pm U_x\right)^2 + \frac{1}{2}\rho_{air} C_{Dy} A \left(U_y\right)^2 \qquad 5.11$$

where ρ_{air} is the density of the ambient air, C_D is the drag coefficient of the vehicle, A is the front cross-sectional area of the vehicle, and C_{Dy} is the dimensionless crosswind aerodynamic drag coefficient for the vehicle.

The rolling resistance is the frictional force acting between the tires and the road. In absence of a downforce imposed by aerodynamic devices (insignificant on all but some classes of race cars), this friction force is the product of the normal force and a friction coefficient:

$$F_R = C_R F_N = C_R W_T \cos\theta \qquad 5.12a$$

where C_R is the coefficient of rolling resistance—the friction coefficient between the tires and the road surface in the direction opposed to vehicle motion.

On a level road (cosθ=1 in Equation 5.12a), recent studies have used a form of the rolling resistance force that accounts for the effects of speed, accounts for the pressure in the tires, and accounts for a dependence on the normal load that is not linear (Kelly, 2002):

$$F_R = C_R W_T = \left[P^{\alpha} W_T^{\beta-1}\left(C_1 + C_2 S + C_3 S^2\right)\right] W_T = P^{\alpha} W_T^{\beta}\left(C_1 + C_2 S + C_3 S^2\right) \qquad 5.12b$$

where P is the pneumatic pressure in the tires [in MPa], S is the vehicle speed [in m/s], and coefficients α, β, and C_1-C_3 are tire-specific constants.

The force imposed by a grade is the force of gravity acting against the motion of the vehicle while driving uphill (or aiding the motion of the vehicle when driving downhill). As illustrated in Figure 5.1, this force is:

$$F_G = \pm W_T \sin\theta \qquad 5.13$$

where the positive sign applies to driving uphill and the negative sign applies when driving downhill.

Combining Equations 5.10-5.13 yields a relationship for the total force opposing the motion of the vehicle:

$$\begin{aligned} F_{res} &= \frac{1}{2}\rho_{air} C_D A (S \pm U_x)^2 + \frac{1}{2}\rho_{air} C_{Dy} A (U_y)^2 + \\ &+ \left[P^{\alpha} W_T^{\beta-1}\left(C_1 + C_2 S + C_3 S^2\right)\right] W_T \pm W_T \sin\theta \\ &= \left(P^{\alpha} W_T^{\beta-1} C_1\right) W_T + \left(P^{\alpha} W_T^{\beta} C_2\right) S + \left(P^{\alpha} W_T^{\beta} C_3 + \frac{1}{2}\rho_{air} C_D A\right) S^2 \\ &\pm \frac{1}{2}\rho_{air} C_D A (U_x)^2 + \frac{1}{2}\rho_{air} C_{Dy} A (U_y)^2 \pm W_T \sin\theta \end{aligned} \qquad 5.14$$

The city and highway fuel economy values on the window stickers of new cars are measurements performed with the vehicle on a chassis dynamometer rather than on an open road, in order to improve measurement repeatability. That is, these measurements of fuel economy are for “road load” operating conditions—driving on a level road with no wind. The resistive force under road load conditions, F_{RL}, is obtained by omitting the wind and grade terms from Equation 5.14 (and simplifying the rolling resistance term):

$$F_{RL} = \frac{1}{2}\rho_{air} C_D A S^2 + C_R W_T \qquad 5.15$$

A force that equals the road load resistive force, but acts in the opposite direction, must be supplied by the vehicle’s engine—through the rest of the drivetrain—at this same tire-road interface in order for the vehicle to operate at steady speed S. When the motive force, F_{mot}, is multiplied by the rolling radius of the driven tires, R_T, the product is the motive torque that must be supplied at the tire-road interface:

$$\tau_{mot} = F_{mot} R_T \qquad 5.16$$

In turn, the required motive power at the tire-road interface is:

$$p_{mot} = 2\pi\tau_{mot} N_{dw} = 2\pi(F_{mot} R_T) N_{dw} = 2\pi R_T N_{dw} F_{mot} \qquad 5.17$$

where N_{dw} is the rotational speed of the driven wheels/tires.

When the rotational speed of the driven wheels/tires is multiplied by the rolling circumference of the driven wheels/tires ($2\pi R_T$, where R_T is the "rolling radius" of the tire), the product is the vehicle speed (S). Performing this substitution into Equation 5.17 yields:

$$p_{mot} = (2\pi R_T N_{dw})F_{mot} = S \cdot F_{mot} \qquad 5.18$$

Therefore:

$$\frac{S}{P_{mot}} = \frac{1}{F_{mot}} \qquad 5.19$$

Under road load conditions for driving schedules that do not include hard acceleration or deceleration transients, the motive force provided by the drive train equals the road load resistive force:

$$\frac{S}{P_{mot,\,RL}} = \frac{1}{F_{RL}} \qquad 5.20$$

Substituting Equation 5.20 into Equation 5.10 yields:

$$FE_{RL} = \eta_e \eta_t \eta_d \left(\rho_f LHV_p\right)\left[\frac{1}{F_{RL}}\right] = \frac{\eta_e \eta_t \eta_d \left(\rho_f LHV_p\right)}{\frac{1}{2}\rho_{air} C_D A S^2 + C_R W_T} \qquad 5.21$$

The overall engine efficiency appearing in Equation 5.21 can be expanded into its components:

$$FE_{RL} = \frac{\left[\eta_{ti}\eta_c\eta_m\right]\eta_t\eta_d\left(\rho_f LHV_p\right)}{\frac{1}{2}\rho_{air} C_D A S^2 + C_R W_T} \qquad 5.22$$

where η_{ti} is the "indicated thermal" efficiency of the engine (the efficiency of the thermodynamic cycle, from the working fluid's perspective), η_c is the "combustion efficiency" (the efficiency of converting the chemical energy of the fuel to thermal energy during the combustion process), and η_m is the "mechanical efficiency" of the engine (the efficiency of overcoming frictional and parasitic losses between the combustion chamber and the engine output shaft).

The indicated thermal efficiency is the actual efficiency of the thermodynamic cycle (as opposed to, for example, the Ideal Otto cycle) and, thus, is a function of engine speed and load.

Therefore, an accurate model for the fuel economy of a vehicle requires accurate models for the efficiencies of the transmission, the differential, the combustion process, the frictional and parasitic losses in the engine, and the thermodynamic efficiency of the engine from the working fluid's perspective, along with knowledge of the aerodynamic drag coefficient, the front cross-sectional area, and the coefficient of rolling resistance of the tires.

5.3 Light-Duty Vehicle Fuel Economy Models

As noted, an accurate fuel economy model requires a lengthy list of accurate submodels. Due to the nature of TxDOT Project 0-5974, the research team decided to break the modeling task into "versions" that would get progressively more accurate.

TxDOT is interested in predictions of fuel economy for two purposes. First, TxDOT needs to predict the fuel economy of any vehicle that travels Texas' roadways for three driving conditions:

1. congestion
2. moderate to heavy use where speed cycles are present (e.g., moderate congestion or arterial roads)
3. free flow (open freeway)

Until driving schedules are available that specify a representative vehicle speed as a function of time for each of these conditions, simplified models had to be developed. Generation of driving schedules for congested freeways and for free flow on highways is planned for the extension of this project.

TxDOT is also interested in predicting the fuel economy of any vehicle as a function of vehicle speed to quantify the fuel economy benefit of driving below the posted speed limit during highway driving. This requires accurate models for both the road load force and the motive force. Such a model is also essential for prediction of the fuel economy of 1) conventional heavy-duty vehicles and 2) both light-duty and heavy-duty hybrid vehicles.

Models that are capable of accomplishing these two goals require knowledge of the driving patterns (vehicle speed as a function of time) and development of models for the engine, transmission, and differential. Our initial model for the fuel economy is class-specific (i.e., aggregated by vehicle class), relies on an assumption about the driving patterns, and is applicable only to light-duty vehicles. This model is discussed in Subsection 5.3.1. A more sophisticated vehicle-specific model for the fuel economy of light-duty vehicles was generated by developing models for the engine, transmission, and differential, as discussed in Subsection 5.3.2. Heavy-duty vehicles are discussed in Section 5.4.

5.3.1 Fuel Economy Model Version 1: An Initial Estimate for Each of DOT's Light-Duty Vehicle Classes

The U.S. DOT classifies light-duty vehicles using the categories listed in Table 5.1. Our initial model provides the city and highway fuel economy for a generic vehicle in each of these classes.

Table 5.1: DOT Light-Duty Vehicle Classifications

CARS		
Class	**Passenger + Cargo Volume [ft^3]**	
Two-Seater	Any 4 wheel vehicle designed to carry only two adults	
Sedans		
Minicompact	<85	
Subcompact	85-99	
Compact	100-109	
Mid-size	110-119	
Large	≥120	
Station Wagons		
Small	<130	
Mid-size	130-159	
Large	≥160	
LIGHT-DUTY TRUCKS		
Class	**Gross Vehicle Weight Rating, GVWR [lb$_f$]**	
	Through Model Year 2007	Beginning Model Year 2008
Pickup Trucks		
Small	<4500	<6000
Standard	4500-8500	6000-8500
Minivans	<8500	<8500
Vans		
Passenger	<8500	<8500
Cargo	<8500	<8500
Sport Utility Vehicles (SUVs)	<8500	<8500
Special Purpose Vehicles	<8500	<8500

Source: http://www.fueleconomy.gov/FEG/info.shtml#sizeclasses

The three available fuel economies for each light-duty vehicle sold in America were used as our initial fuel economy model. On behalf of the National Highway Traffic Safety Administration (NHTSA, an arm of the U.S. DOT), EPA approves test results performed by the manufacturer (and does random confirmatory testing) of each vehicle and then requires the "city" and "highway" fuel economy values (FE_{city} and FE_{hwy}, respectively) for each vehicle to be posted on the "window stickers" of all new light-duty vehicles and these two measures of the fuel economy are also listed in the "Fuel Economy Guide" that is published jointly by the U.S. Department of Energy and the U.S. Environmental Protection Agency and is also available via the web (www.fueleconomy.gov/feg). Here, it should be noted that the Fuel Economy Guide also uses the DOT categories listed in Table 5.1.

Additionally, for calculation of the Corporate Average Fuel Economy, the manufacturers calculate a "composite" fuel economy via:

$$FE_{comp} = \frac{1}{\frac{0.55}{FE_{city}} + \frac{0.45}{FE_{hwy}}} \qquad 5.23$$

Beginning in 2008, the EPA changed the procedure for measuring the “city” and “highway” fuel economy. Before the 2008 Model Year, the city fuel economy was 90% of the fuel economy measured during operation over the light-duty Federal Test Procedure (FTP) driving cycle and the highway fuel economy was 78% of the fuel economy measured during operation over the Highway Fuel Economy Test (HFET) driving cycle, where the fractions (0.90 and 0.78) account for real world factors that decrease fuel economy, such as underinflated tires, rain, and wind. Under the new procedure, the city fuel economy is a weighted average of the fuel economy measured during operation over four driving cycles: 1) the FTP after the vehicle has “soaked” at a temperature in the range of 20-30 ^{o}C (68-86 ^{o}F), often referred to as a 75 FTP (where “75” refers to this driving schedule as revised in 1975 rather than to a convenient rounded average initial temperature), 2) a high speed, hard acceleration driving cycle (the US06), 3) a driving cycle during which the air conditioner is on (the SC03), and 4) the FTP after the vehicle has soaked at 20 ^{o}F, often called the Cold FTP. However, the fuel economy is still dominated by the FTP. Also, the new procedure for estimating the highway fuel economy is to calculate the weighted average over, again, four driving cycles: 1) the 75 FTP, 2) the HFET, 3) the US06, and 4) the SC03. The driving conditions for each of these five tests are listed in Table 5.2

As can be deduced from the data in Table 5.2, the city fuel economy test is primarily a low speed test. Specifically, the FTP, which dominates the city fuel economy, is a driving cycle that is approximately 30 minutes long, and the vehicle is stationary and idling 20% of the time and decelerating to a stop another 20% of the time, with slow accelerations but with a peak speed of 58 mph. Therefore, our research team decided to use the city fuel economy as our initial estimate of the fuel economy for congested driving. Similarly, we decided to use EPA’s highway fuel economy as our initial estimate for the open freeway fuel economy and the composite fuel economy as our initial estimate for arterial driving.

Table 5.2: Summary of the Test Schedules Used to Measure City and Highway Fuel Economy Beginning with Model Year 2008.

Cycle	Avg. Speed (mph)	Max Speed (mph)	Max. Accel. (mph/s)
75 FTP	21	58	3.3
HFET	48	60	3.3
US06	48	80	8.5
SC03	22	55	5.1
Cold FTP	21	58	3.3

Our initial light-duty fuel economy model was generated from the average city and highway fuel economy for each of DOT’s classes (Table 5.1) plus our calculated composite fuel economy for that class. Records from *Automotive News* of national automobile sales by nameplate were analyzed for model years 2002-2008. The vehicles shown in Table 5.3 were chosen based on which models (in each category) sold the most during the last several years. Our research team also took into consideration the vehicle makes most common in that vehicle category, from the Texas VTR data (which provided makes, such as Toyota and Ford, but not models, such as Corolla and Escape).

To generate Table 5.3, the light-duty vehicles were sorted into the various vehicle categories in Table 5.1. In each category, typically two to four car models would dominate the sales. Vans and minivans were <2% of the Texas fleet, so they were omitted as a category. Similarly, subcompact and minicompact cars, two seaters, and special purpose vehicles were omitted as categories. Station wagons and sedans were combined into one category. Station wagon-type cars that are similar in design and shape to their sedan counterparts did not noticeably differ in operating costs. Of those vehicles that were somewhat different from sedans, these "station wagons" were denoted as "crossovers" and are combined with SUVs (light trucks) in Table 5.3. That is, station wagons were re-classified into either the large sedan or small SUV category. Additionally, it was decided that it is preferable to subdivide the SUV category into subclasses: small, mid-size, and large.

Table 5.3: Light-Duty Vehicles Selected for Inclusion in the First Generation TxDOT Vehicle Class Based Fuel Economy Model

CARS AND LIGHT-DUTY TRUCKS			
Class	**Vehicles Chosen as Representative**		
Two-Seaters	<2% of minicompact sales		
Sedans and Similar Station Wagons			
Minicompact	<~3% of national sales		
Subcompact	<~3% of national sales		
Compact	Ford Focus	Honda Civic	Toyota Corolla
Mid-size	Honda Accord	Chevrolet Malibu	Toyota Camry
Large	Chevrolet Impala	Ford Taurus	
Pickup Trucks			
Small	Toyota Tacoma	Ford Ranger	Chevrolet Colorado
Standard	Dodge Ram 1500	Ford F150	Chevrolet Silverado 1500
Minivans	<2% of Texas on-road fleet		
Vans	<2% of Texas on-road fleet		
SUVs and Crossovers			
Small	Ford Escape	Jeep Wrangler	Toyota Rav4
Mid-size	Jeep Grand Cherokee	Ford Explorer	Toyota Highlander
Large	Chevrolet Suburban	Ford Expedition	GMC Yukon

The average fuel economy (city and highway) within each class of vehicles, averaged over each of the two or three vehicles chosen as representative of that class based upon national sales records and Texas VTR data, is a basic input to our initial model for the fuel economy of light-duty vehicles.

The use of this class-specific model is discussed is Section 5.5.

5.3.2 Fuel Economy Model Version 2: Vehicle-Specific Models for Light-Duty Vehicles

Vehicle-specific models were also generated during FY 2009 for TxDOT Project 0-5974. Because the “Fuel Economy Guide” does not provide any information regarding heavy-duty vehicles, separate modeling approaches were taken for each of these two main categories of vehicles. Heavy-duty vehicles are discussed in Section 5.4.

As noted previously, an accurate model for the fuel economy of a vehicle requires accurate models for the efficiencies of the transmission, the differential, the combustion process, the frictional and parasitic losses in the engine, and the thermodynamic efficiency of the engine from the working fluid’s perspective. The techniques our research team developed during FY 2009 for each of these models necessarily differed for light- and heavy-duty vehicles. The model developed for light-duty vehicles is discussed in this subsection. Heavy-duty vehicles are discussed in Section 5.4.

Models for the road load force and for the efficiencies of the transmission, the differential, the combustion process, the frictional and parasitic losses in the engine, and the thermodynamic efficiency of the engine for light-duty vehicles are discussed below.

Road Load Force for Light-Duty Vehicles

In order for the auto manufacturers to demonstrate compliance with emissions standards and to determine the fuel economy of each make of vehicle for calculation of their Corporate Average Fuel Economy, the auto manufacturers must have a method for consistently setting the power absorbed by their chassis dynamometers as a function of vehicle speed.

In the 1970s and 1980s, before the web became widely used, one could order reports from the Motor Vehicle Manufacturers Association (MVMA) that provided the drag coefficient and the front cross-sectional area. Separate reports could be obtained for every light-duty vehicle sold in America. The vehicle manufacturer could then obtain the coefficient of rolling resistance for the tires, inflation pressure, and normal load on each tire from tire test machine data.

The product C_DA was experimentally measured in tests that were conducted in a wind tunnel that did not have a “moving ground plane.” Given the front cross-sectional area of the vehicle, one could then calculate the drag coefficient from the wind tunnel data. However, due to the difference in flow under the car because of the stationary floor in the wind tunnel, and especially because the tires were not rotating and thereby inducing additional aerodynamic drag, this value for C_D was not accurate.

Tire test machines roll the tire and wheel using a belt or drum, the surface of which is engineered to be similar to typical asphalt. The rolling resistance depends on both the properties of the tire and the properties of the road surface. Additionally, both the construction and the compound of the tire affect the rolling resistance, as does the normal load on the tire. Most importantly, the coefficient of rolling resistance is dependent upon the vehicle speed. SAE Recommended Practice J1263 suggests that, unless specific information about the particular tires used is available, the following equation should be used to account for the increase in rolling resistance with increasing speed:

$$C_R = C_R^o\left(1 + C_R^{'} S^2\right) \qquad 5.24$$

where C_R^o is the "velocity independent coefficient of rolling resistance" (this value is the only coefficient of rolling resistance that may be available, if any, and is the value measured at low speed where C_R^o is approximately constant) and C_R' is the "velocity coefficient of rolling resistance" (SAE J1263 suggests $C_R'=50\bullet10^{-6}/(\text{mph})^2 = 2.5\bullet10^{-4}\ s^2/m^2$ if specific information is not available).

Equation 5.24 differs from Equation 5.12a via lack of a term that is linearly dependent upon vehicle speed. A recent report from Michelin (2003) states that the coefficient of rolling resistance for passenger car tires is relatively constant for speeds up to 100 kph (~62 mph) or sometimes 120 kph (~75 mph), after which it increases with increasing vehicle speed. Thus, there was some uncertainty in using tire test machine data for C_R.

Because there was uncertainty and imprecision in the method used to adjust the power absorbed by the chassis dynamometer as a function of vehicle speed, EPA changed the technique for adjusting the road load power. Specifically, EPA began providing the road load horsepower ($=F_{RL}*S$) at 50 mph by performing a relatively simple coastdown test for each model of vehicle. The engineers or technicians would then generate a second order equation of road load power versus vehicle speed that passed through this specified point and also through the origin, with a slope of 0 at zero speed. In the mid-1990s, when EPA decided that emissions certification would also require a high speed, hard acceleration driving cycle (the US06), use of 48 inch diameter chassis rolls became required in order to prevent overheating of the tires, which were deformed too much for sustained operation when using the prior twin small roll chassis dynos. This change in chassis dyno hardware also afforded the opportunity to require use of electric dynos rather than the prior water brake dynos. In turn, the use of electric chassis dynos allowed much more precise control. Therefore, the EPA changed the technique for specifying the power absorbed as a function of vehicle speed. They now provide three vehicle-specific coefficients of the form:

$$F_{RL} = m_e \frac{dS}{dt} + A + B \times S + C \times S^2 \qquad 5.25$$

where m_e is the effective mass of the vehicle (the curb weight of the vehicle divided by the local gravitational acceleration plus the EPA-specified payload of 300 lb_f plus the masses of the rotating wheel assemblies (wheels, tires, hubs, wheel bearings, etc.) and coefficients A, B, and C are obtained from coastdown tests of the vehicle, as performed using SAE Recommended Practice J1263 or J2263.

These coastdown coefficients, along with the "effective test weight" ($ETW = m_e/g$), are available from the EPA (http://www.epa.gov/otaq/crttst.htm) for all light-duty vehicles sold in the U.S. This website provides two sets of coastdown coefficients: Target A, Target B, and Target C plus Set A, Set B, and Set C. The target values were obtained from on-the-road coastdown tests while the Set coefficients were obtained from coastdown tests on a chassis dyno. Thus, the Target coastdown coefficients are the relevant coefficients for on-road fuel economy modeling.

For driving schedules (or driving patterns) that do not involve hard acceleration or deceleration transients, or steep hills, the road load force is equal to the motive force. Therefore, the coastdown coefficients that are available for all light-duty vehicles that are sold in the U.S. can be used to calculate the motive force that must be provided at the tire-road interface in order for the vehicle to travel at any selected speed. Then, via Equation 4.16 the motive torque at the tire-road interface can be calculated. One can then work one's way back through the drivetrain, given models for the differential and transmission, to determine the torque and speed required from the engine, which is the consumer of the fuel.

Drivetrain Models for Light-Duty Vehicles

Transmission, differential, and especially engine models are too complex and technical for the purposes of the body of this project report. Therefore, the models used for the performance and efficiencies of the transmission, differential, and engine in light-duty vehicles are discussed in Appendix G.

5.4 Heavy-Duty Vehicles

The model used for the road load force for heavy-duty vehicles is discussed in Subsection 5.4.1 and the models used for the drivetrain efficiencies for heavy-duty vehicles are discussed in Subsection 5.4.2.

5.4.1 Road Load Force for Heavy-Duty Vehicles: Coastdown Tests

Unlike light-duty vehicles, there are many manufacturers of heavy-duty engines that may be used in heavy-duty vehicles that are assembled by other manufacturers. For example, if one purchases a heavy-duty truck, one can choose the engine from a variety of heavy-duty engine manufacturers. Because of this, and because the same heavy-duty engine can be used in a variety of vehicles and equipment, heavy-duty engines (rather than vehicles) are subjected to emissions standards and the corresponding tests. Furthermore, there are no fuel economy standards for heavy-duty vehicles.

Therefore, the EPA provides data that are useful for fuel economy (and emissions) tests (and models) for light-duty vehicles, but does not provide any data that is useful for calculating the fuel economy of heavy-duty trucks.

Due to the lack of data from EPA for calculating the road load force for heavy-duty vehicles, it was necessary to perform coastdown tests for TxDOT Project 0-5974. The research team used the procedure described in SAE Recommended Practices J1263 and J2263, which are discussed in Appendix G. Coastdown tests were performed on:

1) A TxDOT Ford F150 (a light-duty vehicle, for which the coastdown coefficients are available from the EPA, to serve as a quality assurance reference),
2) A TxDOT Ford F350 (a DOT Class 2B truck: 8,501 - 10,000 lb_f GVWR)
3) A TxDOT International truck (a DOT Class 8A truck; 30,001-60,000 lb_f GVWR) with measurements made for three cases: empty (27,785 lb_f; DOT Class 7, 26,001-33,000 lb_f), weighed-out (44,700 lb_f), and “cubed-out” (36,360 lb_f)
4) A TxDOT “weigh-in-motion” calibration truck (a DOT Class 8B truck: 60,001-80,000 lb_f GVWR) with measurements made for three cases: empty (31,910 lb_f), weighed-out (78,785 lb_f), and “cubed-out” (56,470 lb_f)
5) An 18-wheeler belonging to HEB, with wide single low rolling resistance tires and aerodynamic devices (another DOT Class 8B truck) with measurements made for three cases: empty (28,760 lb_f), weighed-out (81,010 lb_f), and “cubed-out” (55,760 lb_f)

Above, “cubed out” refers to a payload that completely fills the trailer with boxes or crates of cargo that is not so heavy that the maximum cargo weight is achieved. The cubed-out weights used for the coastdown tests of the various heavy-duty trucks were determined from TxDOT’s weigh-in-motion data.

The F150 was included in the coastdown test matrix as a quality assurance check on our coastdown test procedure, which is explained in Appendix D. Because the F150 is a light-duty vehicle, its coastdown coefficients are available from the EPA. We generated our own coastdown coefficients for the F150 for comparison against EPA’s values. Reasonable agreement between the two would indicate that our coastdown test results are valid.

The research team was fortunate in that a new toll road, just south of Austin, was in the final stages of completion and was expected to be opened in late spring 2009. TxDOT arranged and facilitated with the construction group for the researchers to be able to utilize this facility—as portions of the roadway were completed—to conduct the coastdown tests. The initial coastdown test took place on December 2, 2008 and began with two small truck types (equivalent to an F150 and an F350). Unfortunately there was not enough road to coast to an absolute stop, but this test did provide the researchers with an insight into how the tests would run and to expect the unexpected. Figure 5.2 is a map of the toll road. The coastdown tests ran approximately between Crane Road and just beyond FM1625. This provided the trucks with spaces at the end of each trip to be able to turn around and perform the coastdown test again in the opposite direction but in the same lane.

Source: TxDOT

Figure 5.2: SH 45

By March 2009 enough roadway had been developed such that coastdown tests could again begin. During March and April 2009, 136 coastdown tests were conducted for the five types of trucks specified above. Figure 5.3 shows the weigh-in-motion truck, which has a series of concrete blocks that can be taken off to reduce the weight on this truck. Figure 5.4 shows how these blocks are tied to the truck.

Figure 5.3: TxDOT's Weigh-in Motion Truck- view from the front

Figure 5.4: TxDOT's Weigh-in Motion Truck- view from the side

The research team also greatly benefited from HEB cooperation on the study coastdown tests. The testing of HEB truck and trailers is discussed in some detail below to provide a "flavor" for the methodology.

During the course of the research, the research team had met with HEB to gather data on operating costs and fleet composition to calibrate the vehicle operating cost desktop model. HEB kindly offered to supply trucks and trailers for the purposes of completing the coastdown tests with vehicles that they were currently operating over the highway, and had the new wide-based (sometimes called super single) tires which TxDOT does not use. This was critically important for ensuring that the model data had current data from trucks, trailers, and tires that were utilized by many of the heavy-duty fleet operators who operate over the TxDOT network. HEB also provided vehicles that had different weight variations. One trailer was fully laden to the top permissible weight allowed on TxDOT's network at ~80,000 lb_f, one vehicle was cubed out at ~56,000 lb_f, and one was empty (~29,000 lb_f). This would also replicate the types of loads and weights that are currently moving on TxDOT's system. These were determined from reviewing TxDOT's weigh-in-motion data, as illustrated in Figure 5.5.

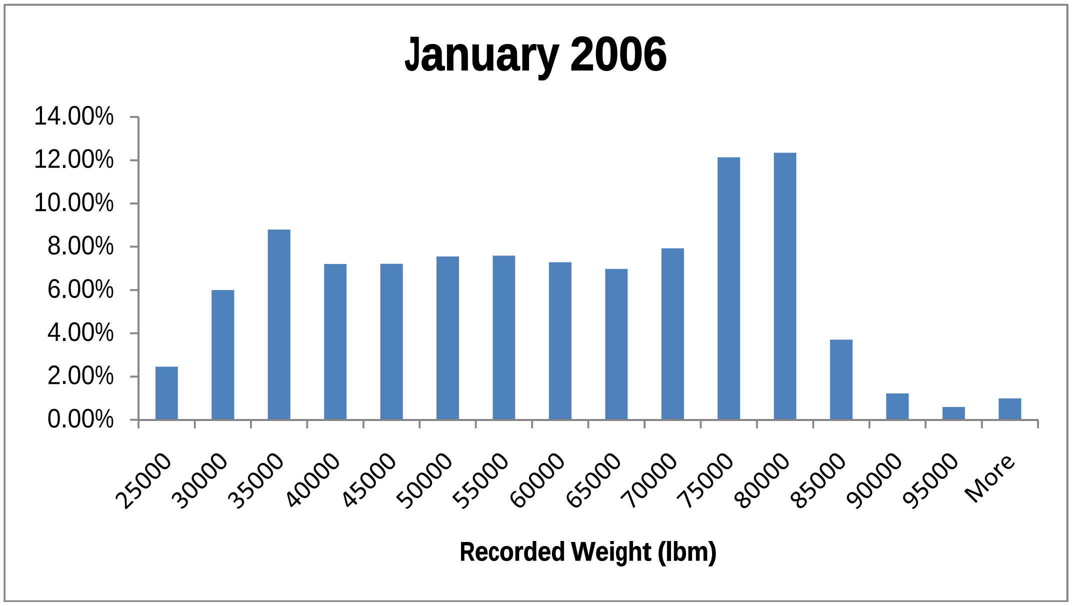


Figure 5.5: Weigh-in Motion Results for EPA Class 8 Trucks

The research team also requested that the HEB trucks and trailers have new tires, with wide singles on all axles except the steering axle. The steering axles were requested to also have new tires, and should be the same for all three vehicles. Figure 5.6 shows the engine of one of the HEB trucks.

Figure 5.6: Engine in an HEB truck

The UT research team and the HEB team arrived at the test site on SH 45 SE at 8.30 a.m. on Sunday, April 19, 2009 to conduct coastdown tests. The team at the site this day included Robert Harrison (Research Supervisor), Lisa Loftus-Otway, Murat Ates, Dana Welter, and Nathan Hutson from CTR; Don Lewis and Duncan Stewart from TxDOT, and Mike Moynihan (plus four others) from HEB. The tests were also filmed by a camera crew from the UT School of Engineering.

As previously noted, HEB supplied three trucks—each at a different loaded weight—to participate in these tests. Figure 5.7 shows one of the HEB trucks.

Figure 5.7: Test Activity using an HEB tractor-trailer

First, the researchers set up the weather station. The weather station comprises an anemometer attached to a standing pole at approximately 4.5 feet high (Figure 5.8).

Figure 5.8: Weather station

Figure 5.9 shows the weather station monitor itself. This was used to monitor wind speed, wind direction, and temperature during the test (as well as a host of other measurements). The researchers also kept a tabulation (wind speed and direction was taken every minute) on these three metrics throughout the duration of the coastdown tests.

Figure 5.9: Weather station monitor

Next the research team explained to the HEB team the protocol for how the tests were to be carried out. Simply put, the trucks would start at a point on the route, accelerate to 65 mph, engage the vehicle into neutral, and then coast to a standing stop. This would then be repeated in the reverse direction in the same lane to obtain matched pairs.

The research team along with HEB personnel then proceeded to weigh the trucks and trailers. Figure 5.10 shows the portable scales that were supplied by TxDOT. Figure 5.11 shows the weighing process taking place with the tires and axles being placed over these scales. Figure 5.12 shows the truck leaving scales after weighing two axles.

Figure 5.10: TxDOT's portable scales

Figure 5.11: Weighing one of the truck axles

Figure 5.12: Truck leaving scales after weighing two axles

The tests then began. Starting points at both ends of the route were marked out with cones and the fully laden truck was the first truck to begin the tests. The tests began at 11:28 a.m. The first run started from the west side of the toll road and ran eastwards towards SH 130. The truck accelerated to 65 mph, the driver put the transmission into neutral, and the truck then coasted to a standing stop. After the truck came to a complete stop, data regarding vehicle speed as a function of time during the coast was downloaded to a laptop computer. The truck turned around, drove eastbound to the east end starting point, stopped, and then replicated the same process. This was repeated five more times so that six matched pairs were created. This same metholdology was done for each truck.

CTR recorded data from the vehicle's on-board computer using a CAN/BIS data logger and GPS data logger that included vehicle speed, engine rpm, and fuel flow rate with time and GPS altitude and location. The time recording interval was 1 second. The tests took all day to complete, with researchers wrapping up at 18:31 hours.

Similar tests were performed using the other trucks, all of which were TxDOT vehicles. The coastdown coefficients obtained from these tests are provided in Table 5.4. The coastdown coefficients shown in Table 5.4 are tentative values. SAE Recommended Practices J1263 and J2263 specify a maximum grade of 0.5% whereas the maximum grade on portions of SH 45 that were used for the coastdown tests was 0.9%. Also, SAE Recommended Practices J1263 and J2263 specify a maximum wind gust of <10 mph, but the wind speed was higher than 10 mph for some of the tests. The research team is developing techniques for correcting the coastdown data for these problems. Coastdown coefficients were not obtained for the F350 due to a data communication problem between the F350 on-board computer and the laptop computer. The research team will resolve this difficulty during the research extension of this project.

Table 5.4: Coastdown Coefficients Developed During TxDOT Project 0-5974
(Tentative results while methods for correcting for grade and wind are being developed)

	Total Weight $[lb_f]$	Coastdown Coefficients		
		A	B	C
TxDOT F150 (DOT Class 2A)	6,054	47.2	-1.6	0.094
TxDOT F350 (DOT Class 2B)	9,505	NA	NA	NA
TxDOT DOT Class 8A truck				
empty	27,785	615.8	-24.0	0.534
"cubed out"	36,360	569.4	8.0	-0.080
"weighed out"	44,700	607.4	12.3	-0.094
TxDOT DOT Class 8B truck				
empty	31,910	307.0	5.8	0.008
"cubed out"	56,470	678.9	-4.2	0.181
"weighed out"	78,785	1797.4	-83.8	1.472
HEB DOT Class 8B truck				
empty	28,760	368.3	-4.8	0.292
"cubed out"	55,760	419.1	-7.5	0.519
"weighed out"	81,010	2506.5	-121.3	2.012

5.4.2 Drivetrain Models for Heavy-Duty Vehicles

As previously noted for the models for the engine, transmission, and differential of light-duty vehicles, these models are too complex and technical to be of interest to the general reader. Therefore, the models used for the efficiencies of the transmission, differential, and engine in heavy-duty vehicles are discussed in Appendix F. However, a notable difference between the light-duty and heavy-duty models is that we used a commercial software package, AVL Cruise, as a key component of the heavy-duty modeling.

5.5 User's Guide to the Vehicle-Specific Fuel Model

The fuel economy model itself is of interest independent of the total vehicle operating cost model. Therefore, it is available as a standalone end product of TxDOT Project 0-5974. As noted previously, two fuel economy models were developed during FY 2009 for TxDOT Project 0-5974. The vehicle class based model was incorporated in the overall Vcost model, the use of which is discussed in Section 6.10. The vehicle-specific model is discussed in this section.

Figure 5.13 is a screenshot of the opening page that is displayed to the user of the vehicle-specific fuel economy model. The user will click on either the picture of a light-duty vehicle or a heavy-duty vehicle to select the category of vehicle for which the user is interested in examining the fuel economy.

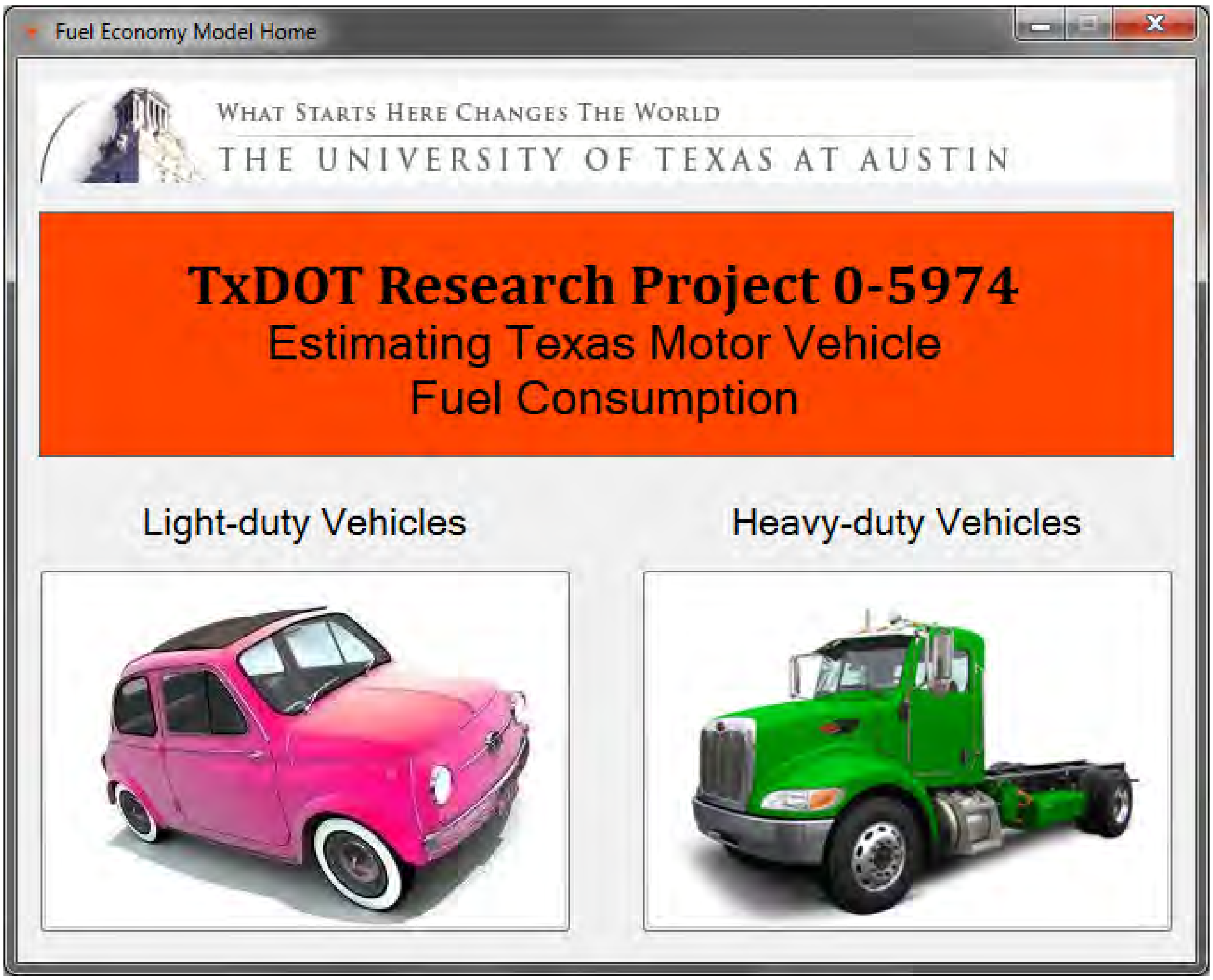


Figure 5.13: Input page for the vehicle-specific fuel economy model

Figure 5.14 is a screenshot of the second page that is displayed if the user of the vehicle-specific fuel economy model selected the "Light-Duty Vehicles" button from the opening page.

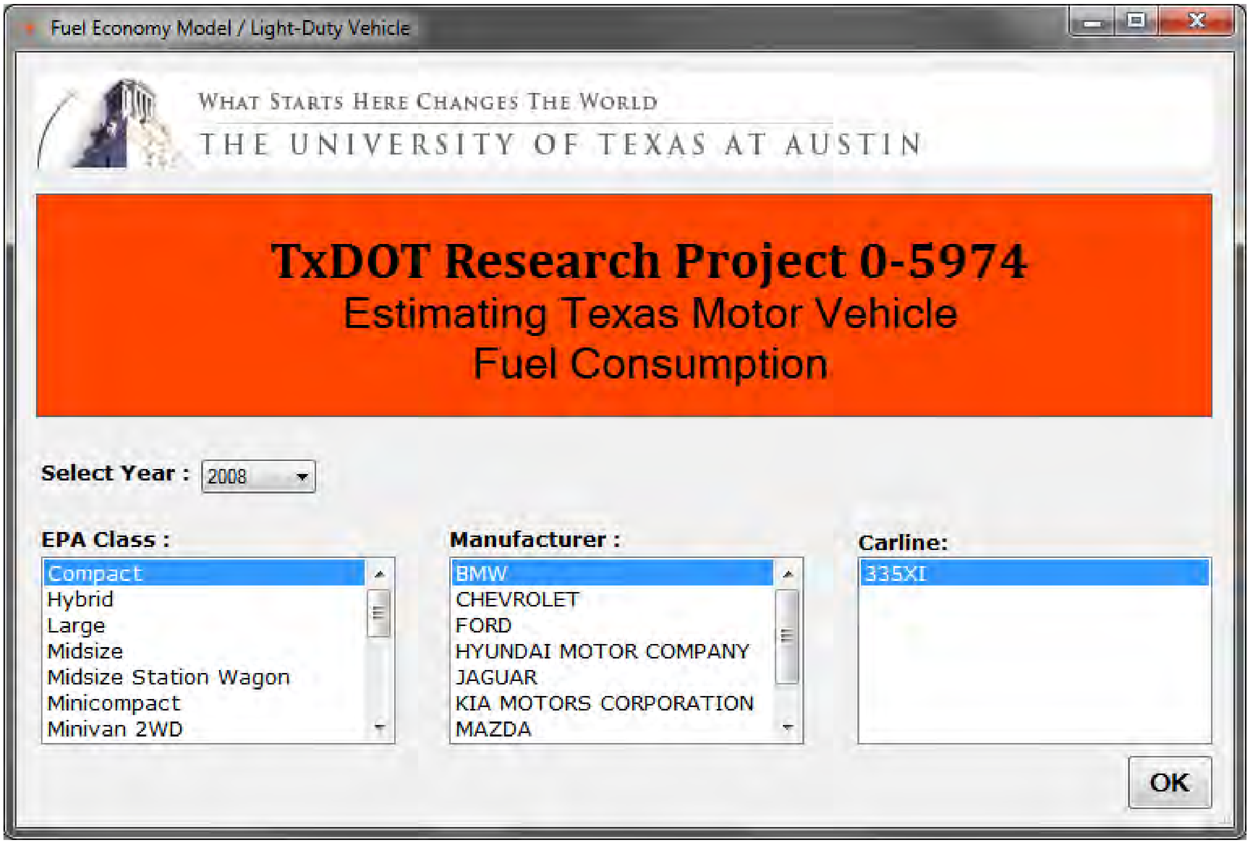


Figure 5.14: Second page if the user selects "light-duty vehicles" from the opening page of the vehicle-specific fuel economy model

On this page, the user will use scroll down menus to select 1) the model year of the specific vehicle of interest, 2) the US DOT vehicle class in which the specific vehicle of interest is categorized, 3) the vehicle manufacturer, and 4) the "carline" for the vehicle of interest. An example of a selection that the user can make is shown in Figure 5.14: a 2008 compact vehicle made by BMW. BMW had only one car platform in the compact class in 2008, the BMW 33SX1. Figure 5.15 is a screenshot example if the user selects a 2007 standard size four-wheel drive (4WD) pickup made by Ford. In this case, there are two vehicles in this category: the F150 and the Ranger. In Step 1, the user can currently select from model years 2003-2008. During the extension of TxDOT Project 0-5974, the research team will add both newer and older vehicles to the data base if TxDOT is interested in this expansion. Step 2 is needed because there are currently 1,287 combinations of makes and models of light-duty vehicles in the data base within the vehicle-specific fuel economy model. For example, there are 265 light-duty vehicles in the 2008 data base alone. After the user makes the selections from the pull down menus, he or she must then hit the "OK" button.

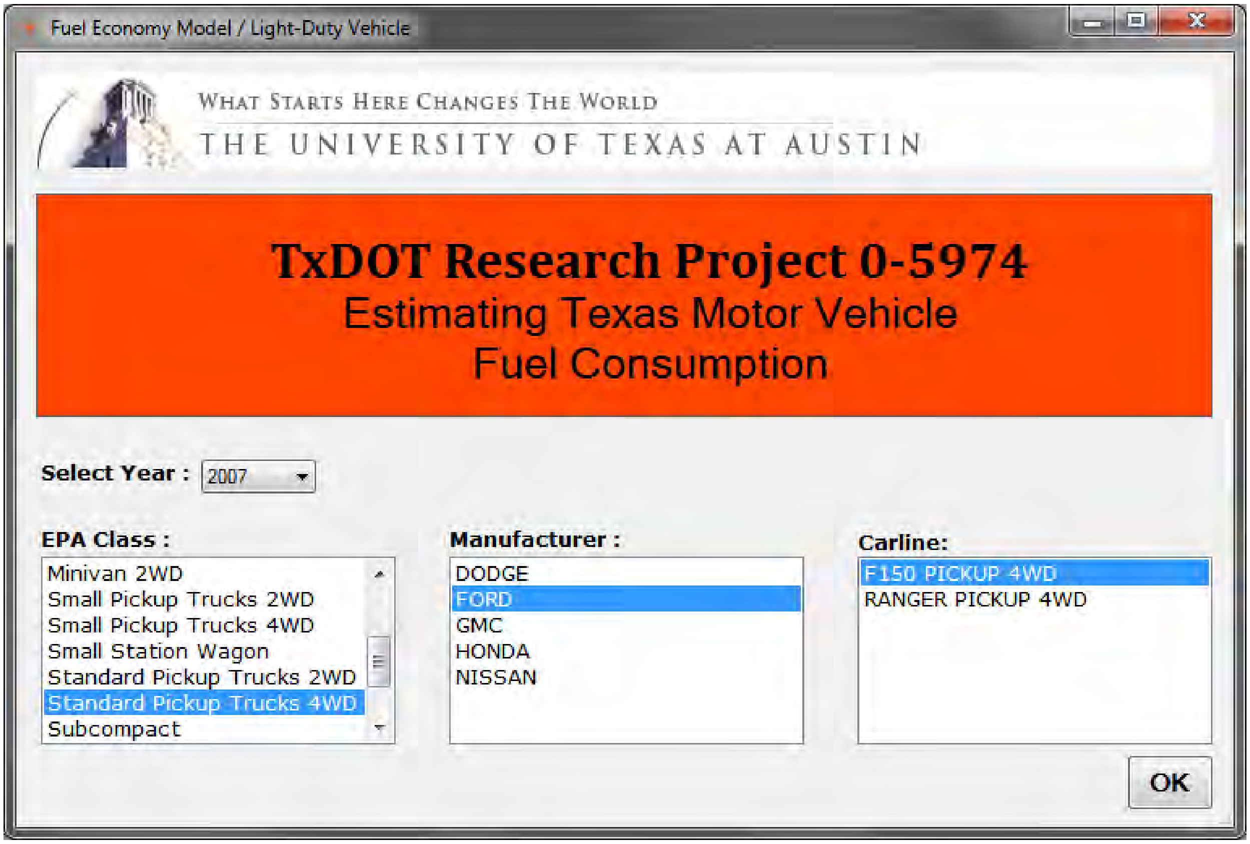


Figure 5.15: Another example of the second page for light-duty vehicles, illustrating a different vehicle selection for analysis using the vehicle-specific fuel economy model

Figure 5.16 is a screenshot of the third page that is displayed if the user of the vehicle-specific fuel economy model selected light-duty vehicles from the opening page and then identified the specific vehicle of interest on the following screen. The user will click on the button that will allow the user to examine either the fuel economy over a drive cycle (vehicle speed as a function of time) or to examine the fuel economy as a function of cruising speed for the vehicle that the user has already specified.

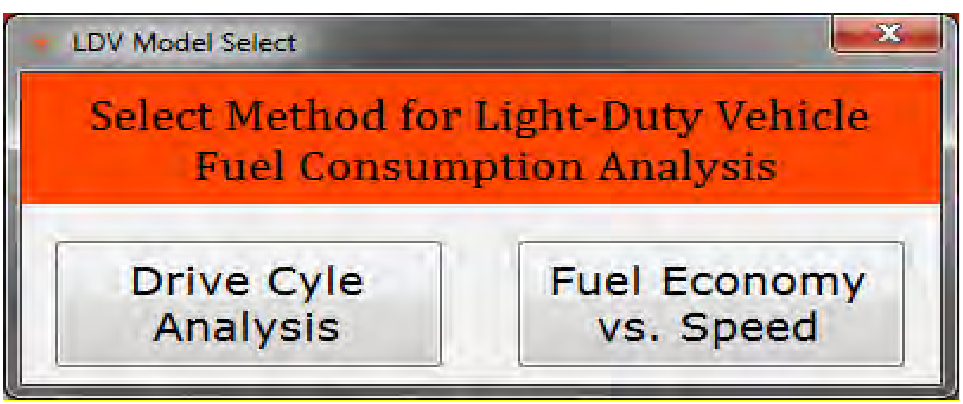


Figure 5.16: Third page if the user selects "Light-Duty Vehicles" from the opening page of the vehicle-specific fuel economy model and then supplies the required information about the vehicle on the following screen

As illustrated in Figure 5.17, the screen will then display the vehicle that has been selected. The user must input the fuel price and hit the "Start" button.

Figure 5.17: Fourth page if the user selects "Drive Cycle Analysis" from the third page after specifying the vehicle of interest on Page 2 (2007 standard size pickup 4WD Ford F150) after selecting "Light-Duty Vehicles" on the opening page

As illustrated in Figure 5.18, the vehicle-specific fuel economy model will then display the city and highway fuel economy for this specific vehicle and the fuel cost per 100 miles of travel over both driving schedules.

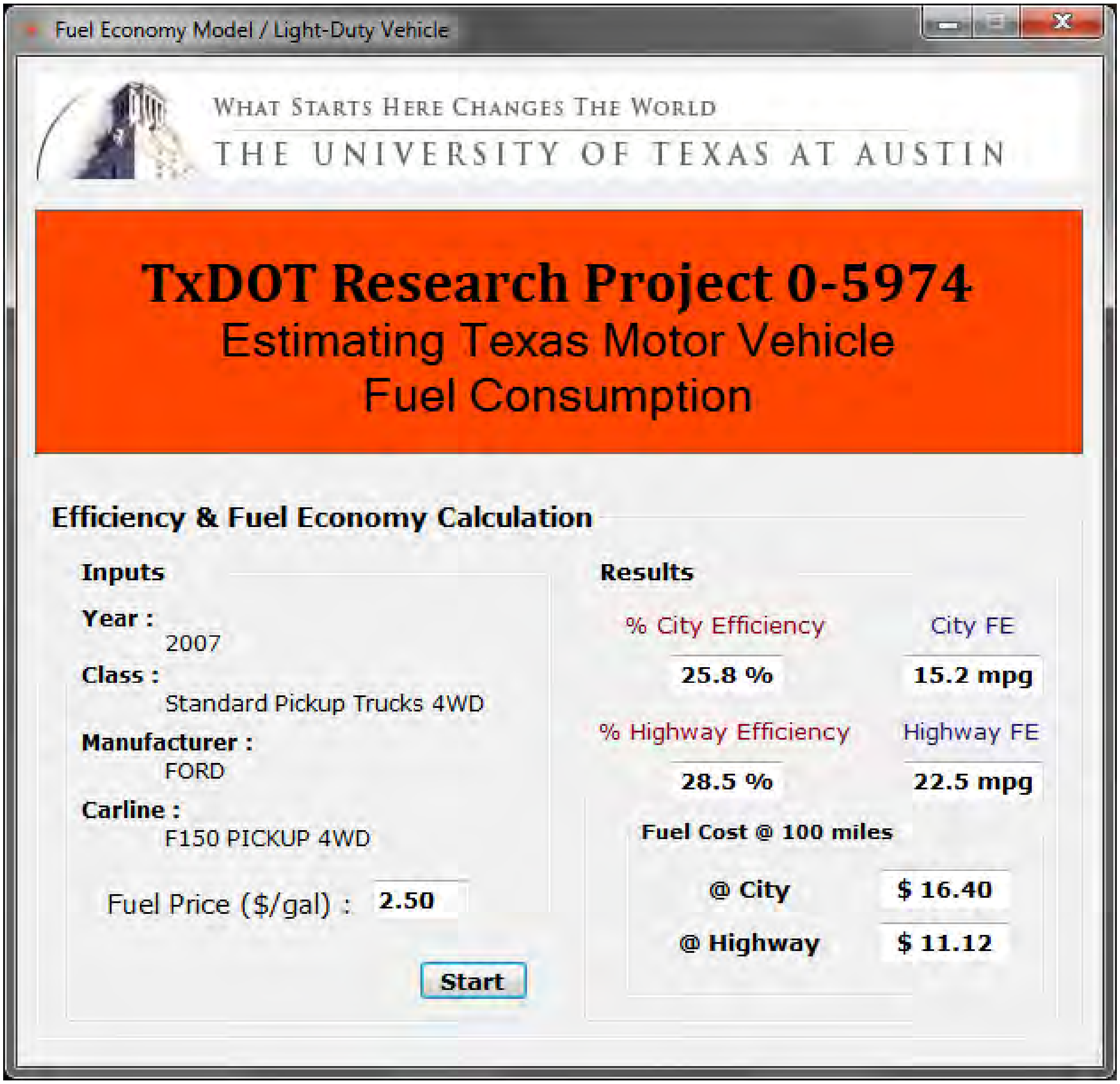


Figure 5.18: The appearance of the fourth page after the user has input a fuel price of $2.50 per gallon and hit the "Start" button

The screen will also display the average drivetrain efficiency for this specific vehicle during operation over both the city fuel economy and the highway fuel economy test cycles. As explained in Subsection 5.3.1, beginning in Model Year 2008 (the data base for the vehicle-specific fuel economy model consisted solely of MY 2008 light-duty vehicles as of the end of FY 2009), the city fuel economy is a weighted average of the fuel economy for operation over four driving cycles and the highway fuel economy is also a weighted average over four cycles, with a total of five different driving schedules required to make the necessary calculations. Each of these driving cycles is a schedule of vehicle speed as a function of time every second with each individual driving cycle lasting up to about one-half hour. To determine the efficiencies displayed on the fourth page, a simplified version of Equation 5.21 was used. Specifically:

$$FE_{RL} = \frac{\eta_e \eta_t \eta_d \left(\rho_f LHV_p\right)}{\frac{1}{2}\rho_{air} C_D S^2 + C_R W_T} = \frac{\eta_{dt}\left(\rho_f LHV_p\right)}{A+B \cdot S+C \cdot S^2} \qquad 5.26$$

Given the coastdown coefficients (A, B, and C in Equation 5.26) and fuel properties ($\rho_f LHV_p$ in Equation 5.26) for the specific light-duty vehicle selected (again, there were 256 MY 2008 light-duty vehicles in the data base as of the end of FY 2009), each specific "virtual" vehicle was "driven" through all 5 driving schedules via a second-by-second model, with an initial guess for the overall drivetrain efficiency ($\eta_{dt} = \eta_e \eta_t \eta_d$ in Equation 5.26) that was iterated to convergence on the actual city or highway fuel economy in the data base. The average city and highway fuel economy and corresponding drivetrain efficiencies for all vehicles in this category are also displayed on this screen.

During FY 2010, the research team will develop driving schedules that represent congested (rush hour) operation on a freeway and another driving schedule for free flow freeway driving. Once these driving schedules (driving cycles) have been developed, this page of the vehicle-specific fuel economy model will also display the fuel economy and overall drivetrain efficiency for operation over these driving schedules.

If the user has accidentally input a value into the sixth page after selecting "Drive Cycle Analysis" that cannot be correct, an "Error Screen" will pop up, as illustrated in Figure 5.19. When the user hits the "OK" button, the prior screen will reappear so that the user can correct the mistake.

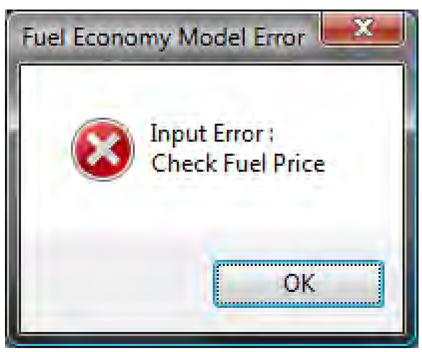


Figure 5.19: Error Screen when an input error is detected

If the user of the vehicle-specific fuel economy model selects "Fuel Economy vs. Speed" from Page 3 (rather than selecting "Drive Cycle Analysis," the use of which was previously discussed), the screen the user will be taken to is illustrated in Figure 5.20.

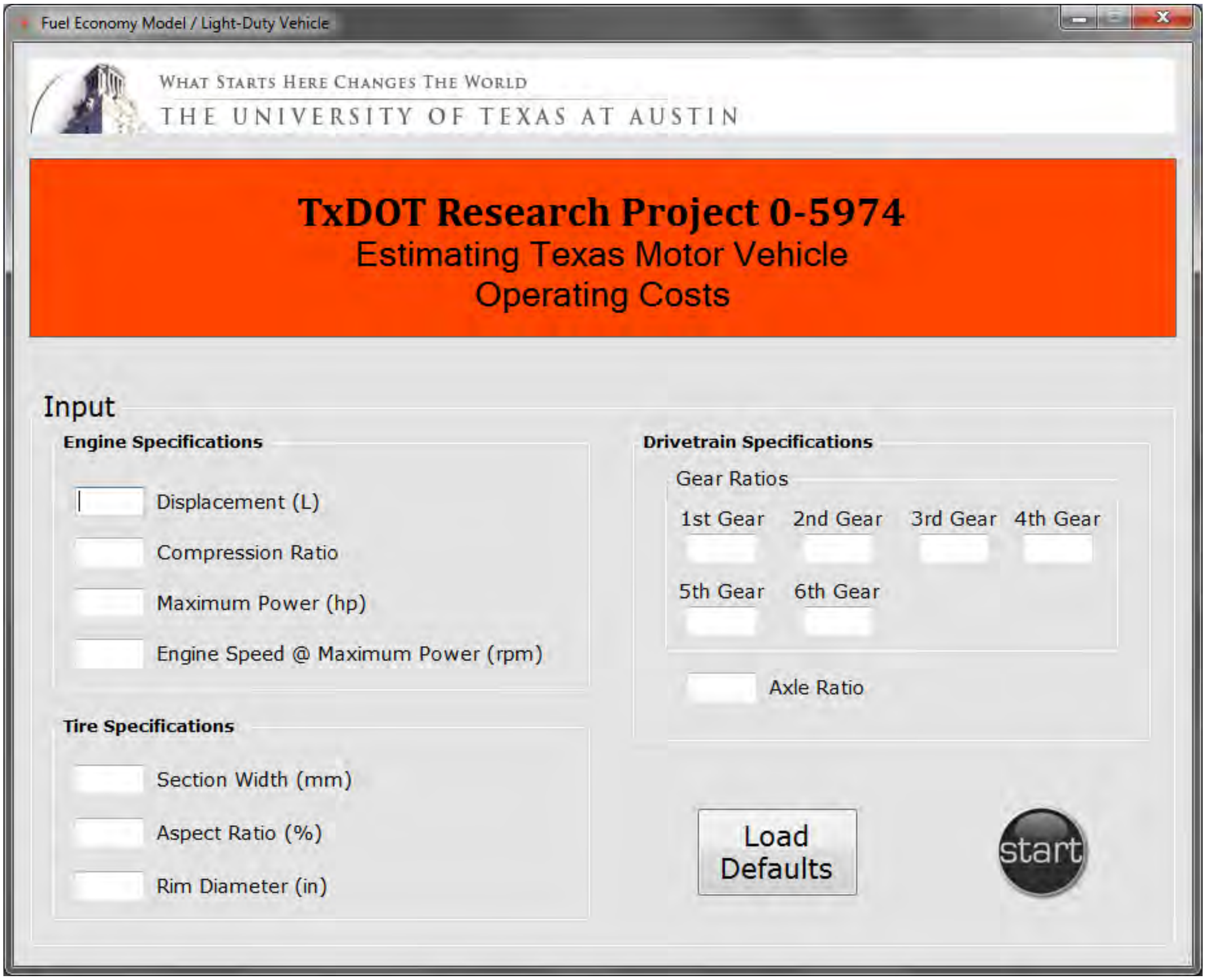


Figure 5.20: Fourth page if the user selects "Fuel Economy vs. Speed" from the third page for light-duty vehicles

After the user fills in the boxes within this input page, it will be similar to the example illustrated in Figure 5.21.

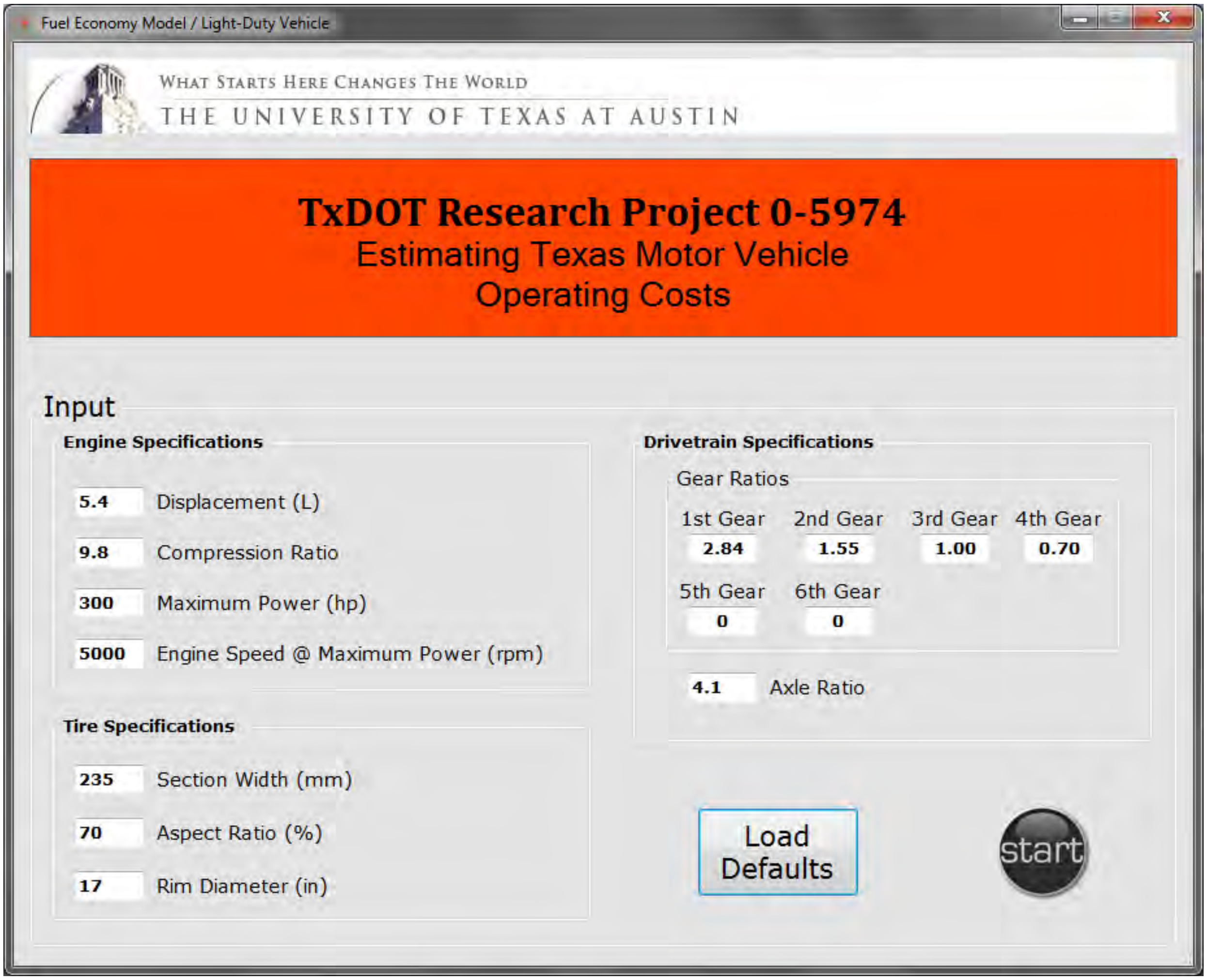


Figure 5.21: Example of how to fill-in the drivetrain input page (Page 4) of the vehicle-specific fuel economy model after selecting "Fuel Economy vs. Speed" from Page 3 for light-duty vehicles and identifying a specific vehicle on Page 2

The required inputs are the displacement and compression ratio of the engine, the rated power (input in the "maximum power" box), the engine speed that corresponds to maximum power, the peak torque of the engine, the engine rpm that corresponds to peak torque, the gear ratios of the transmission, the differential gear ratio (in the "axle ratio" box on the input page), and three boxes for "Tire Specifications." These three boxes ask the user to input the tire section width in mm, the tire aspect ratio in percent, and the rim diameter in inches. All of the required drivetrain data is available in the vehicle owner's manual. All of the required tire data is available on the sidewall of the tire as the "tire size," although it is not labeled as "tire size" on the sidewall. Light-duty vehicles will have a tire size specification similar to P235/70R17. The leading letter, P in the case of this example, designates the type of vehicle this tire is to be used on, but is not of interest for the fuel economy model. The following three numbers are the "section width" of the tire—the lateral length of the tire in millimeters (235 mm in this example). The model user inputs these three numbers in the "section width" box. The following pair of numbers is the aspect ratio of the tire—the ratio of the sidewall height to the section width in percent (70% of 235 mm in this example). The model user inputs these two numbers in the "aspect ratio" box. The following letter (R in the case of this example) denotes whether the tire is a radial or a bias ply tire, but this information is not required for the fuel economy model. The final pair of numbers (17 in this example) is the wheel (also called the rim) diameter in inches. The model user inputs this number in the "rim diameter" box. The vehicle-specific fuel economy model uses the tire specifications to estimate the rolling radius of the drive tires. The tire specifications are used within the vehicle-specific fuel economy model to estimate the rolling radius of the tires.

After filling in the drivetrain input page and hitting the "Start" button on Page 4, the vehicle-specific fuel economy model will return a graph of fuel economy as a function of cruising speed, such as that shown in Figure 5.22. The user can then make a change in the drivetrain description, such as the "axle ratio," to see how this affects the vehicle's fuel steady-state economy, as illustrated in Figure 5.23.

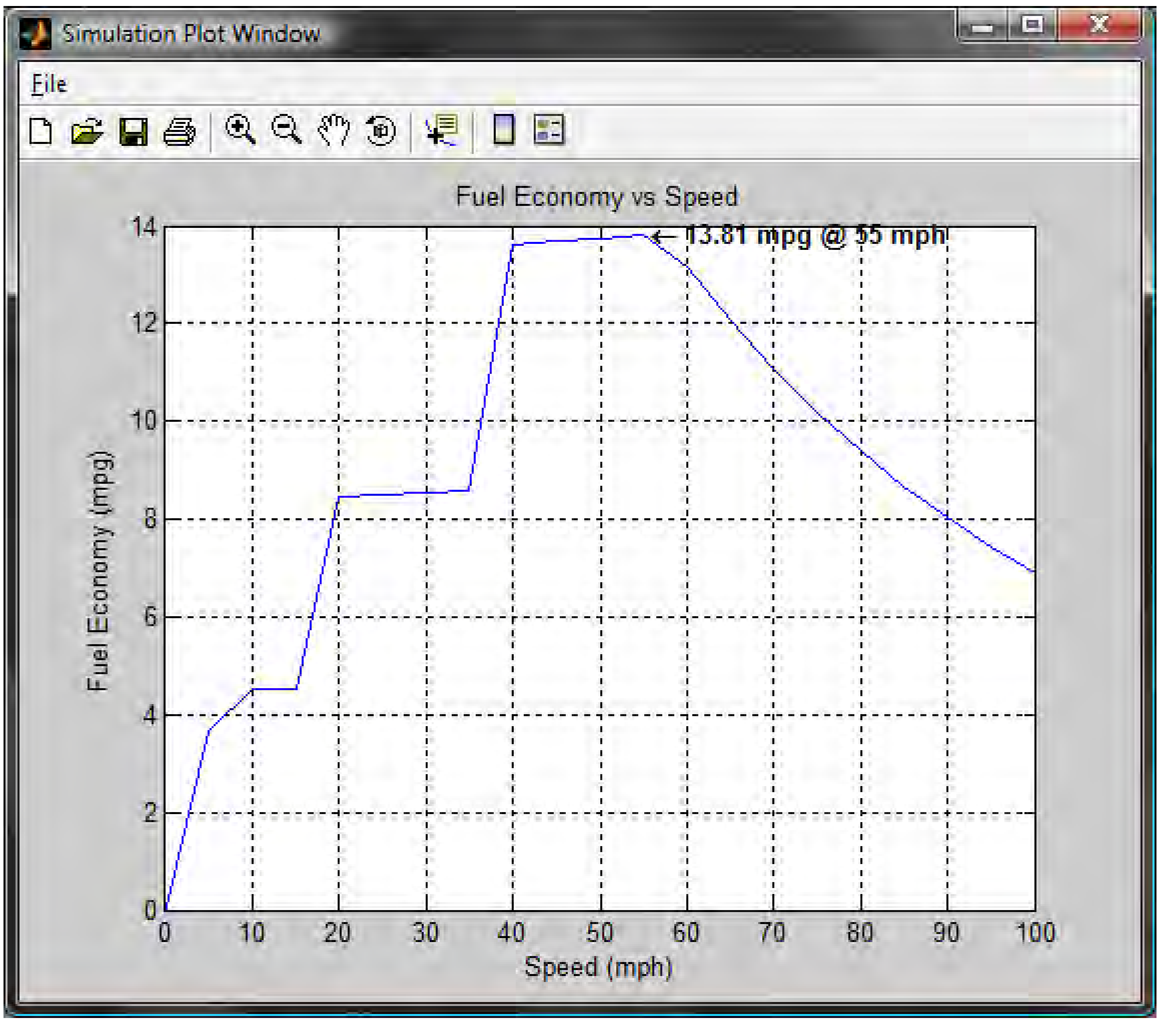


Figure 5.22: Example of the output page (Page 5) of the vehicle-specific fuel economy model after selecting "Light-Duty Vehicles" from the opening page, identifying the specific vehicle on Page 2, selecting "Fuel Economy vs. Speed" from Page 3, filling in the required drivetrain parameters on Page 4, and hitting the "start" button on the input page (Page 4)

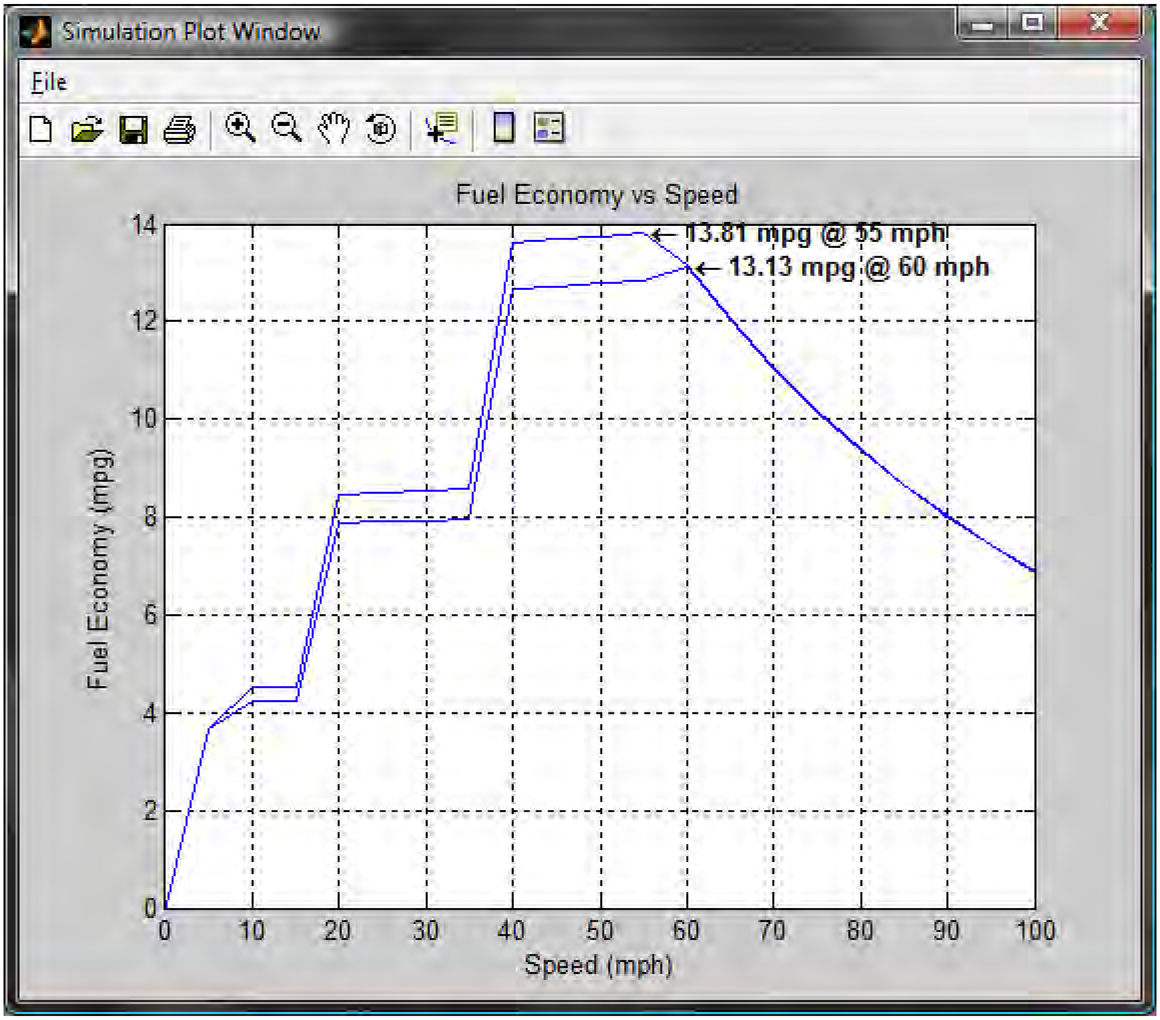


Figure 5.23: Example of the output page after the user has specified two separate drivetrains for comparison

If the user elects to examine a heavy-duty vehicle instead of a light-duty vehicle from the opening page (illustrated in Figure 5.13) of the vehicle-specific fuel economy model, the second page under heavy-duty vehicles is shown in Figure 5.24.

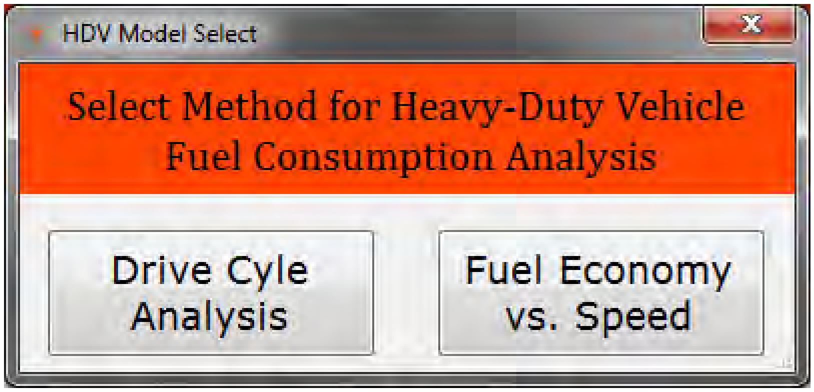


Figure 5.24: The second page after the user has selected "Heavy-Duty Vehicles" from the opening page of the vehicle-specific fuel economy model

As was also the case for light-duty vehicles, the user can select between a drive cycle analysis and examining fuel economy as a function of cruising speed. As of the end of FY 2009, the "Drive Cycle analysis" button is inactive. This button will function correctly after the research team has generated driving patterns for congested freeway driving and for free low operation on the freeway during the research extension of TxDOT Project 0-5974.

After the user has selected to examine fuel economy as a function of vehicle speed from Page 2 for heavy-duty vehicles, a screen similar to that shown in Figure 5.25 will appear.

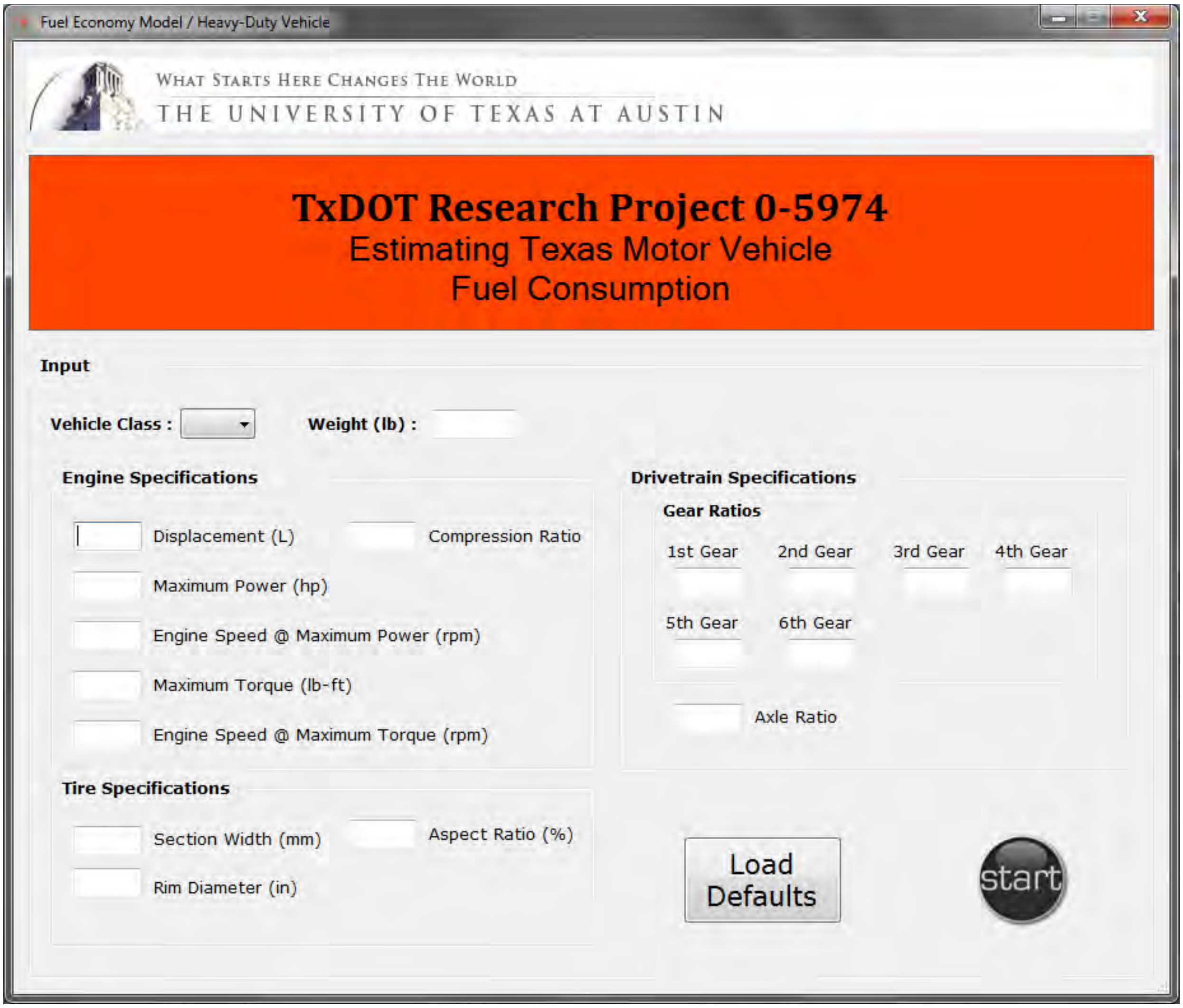


Figure 5.25: The third page after the user has selected "Heavy-Duty Vehicles" from the opening page of the vehicle-specific fuel economy model and then selected the "Fuel Economy vs. Speed" button from the second page

On this page, the user will be required to fill in several boxes. The user will first select the heavy-duty vehicle class from a pull down menu. The user will also fill in several boxes. These include the loaded vehicle weight (in lb_f), the differential gear ratio (axle ratio), the engine displacement (in liters), the engine's compression ratio, the peak horsepower and corresponding engine speed (rpm), the peak torque and corresponding rpm, the tire specifications, and the transmission gear ratios. (Only six speeds are shown in Figure 5.25, but the research team will develop a method to allow the user to input up to eighteen speeds during the project extension, and the research team will also develop a method to allow the user to select the type of transmission from a menu that will include manual, automatic, automatic with lock-up torque converter, or a "semi-automatic," which is an automatically shifted manual transmission).

An example of a filled in input page is provided as Figure 5.26. The user will then hit the "Start" button on that page.

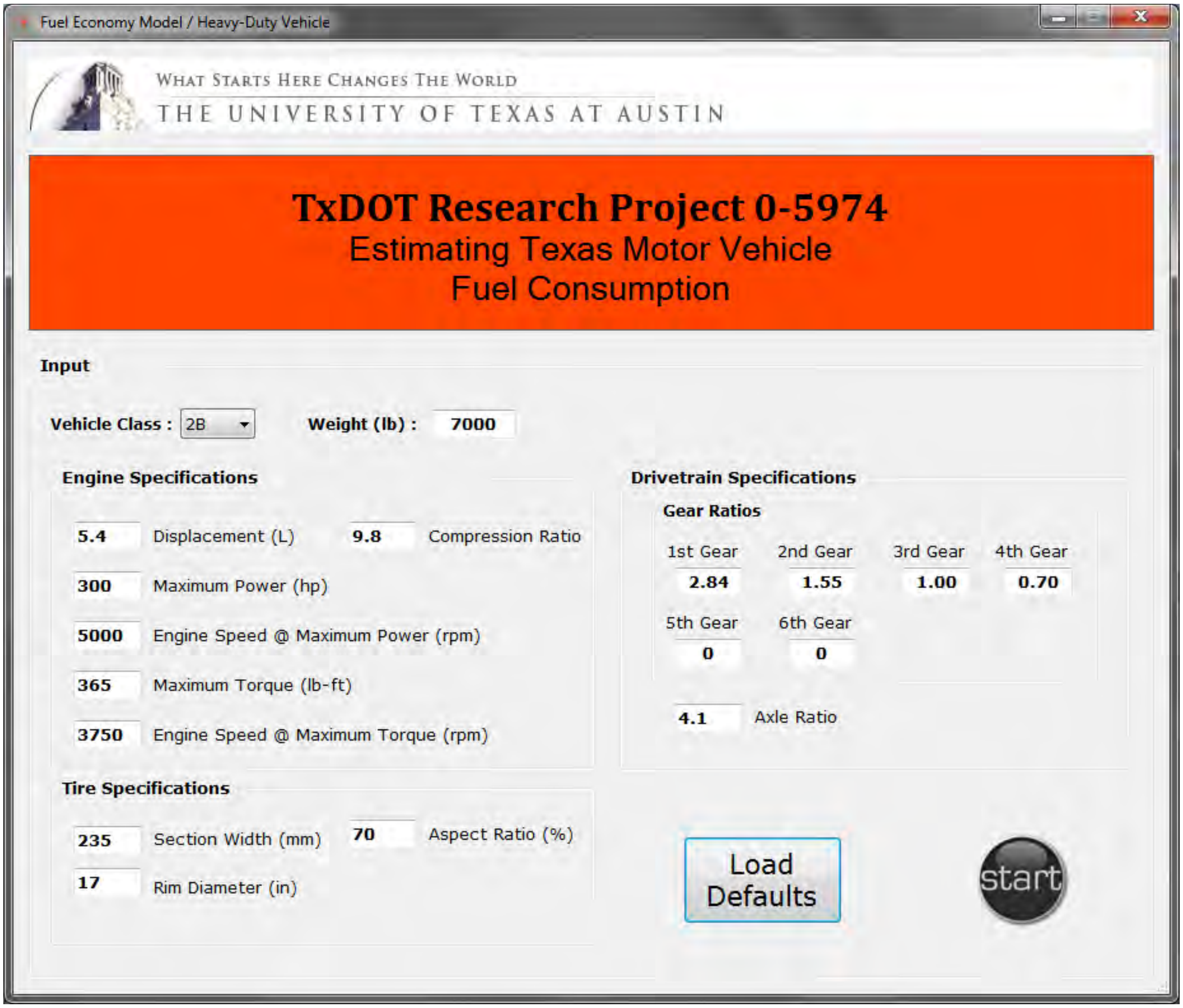


Figure 5.26: Example of the third page for heavy-duty vehicles after the user filled in the data requirements

Figure 5.27 is an illustration of the appearance of the output page from the vehicle-specific fuel economy model for heavy-duty vehicles. The user will be able to examine how the fuel economy varies with cruising speed and the cruising speed that yields the best fuel economy for this specific heavy-duty vehicle.

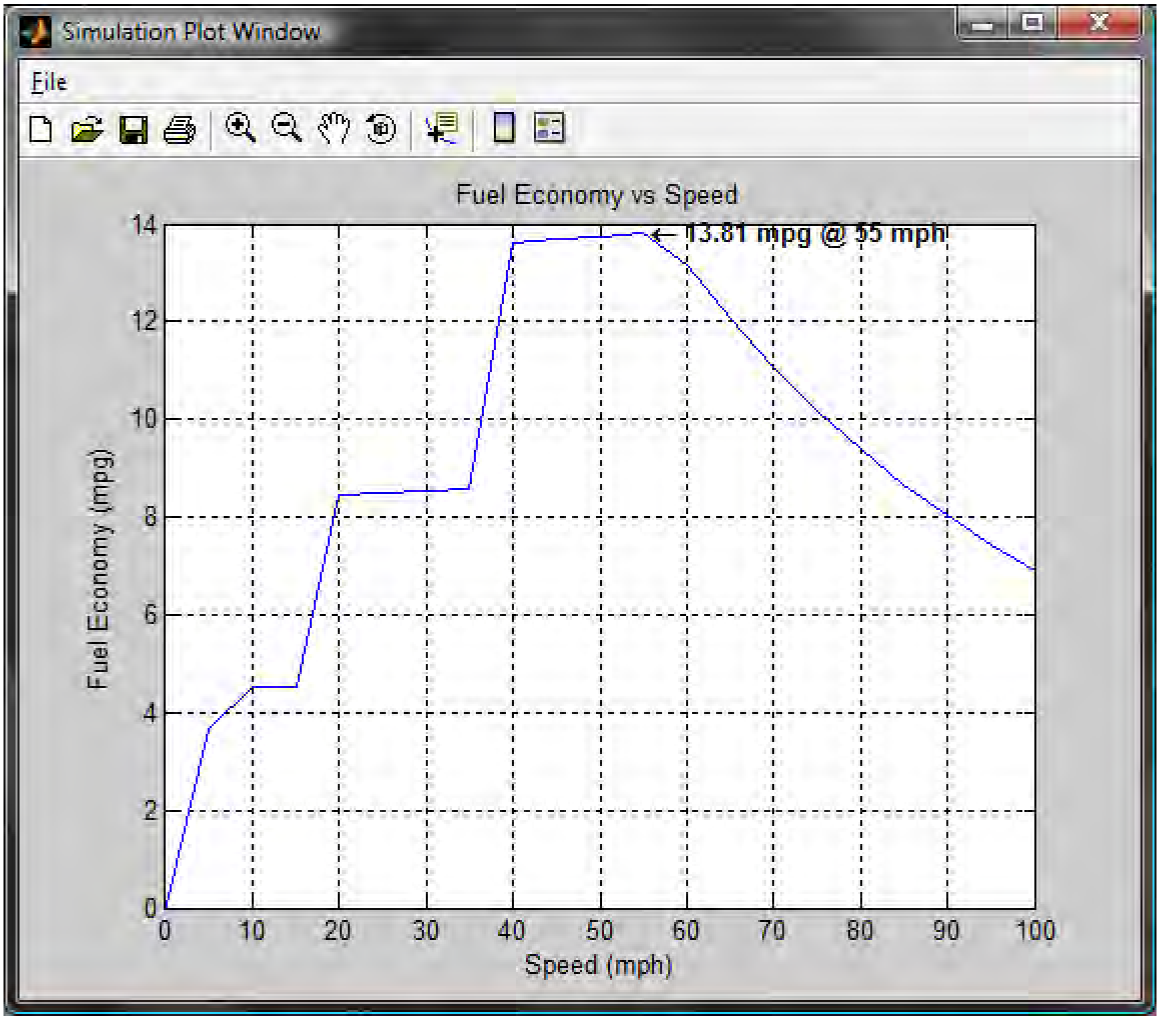


Figure 5.27: Example of the output page (Page 4) of the vehicle-specific fuel economy model after selecting "Heavy-Duty Vehicles" from the opening page, selecting "Fuel Economy vs. Speed" from Page 2, and entering specific vehicle information on Page 3

Chapter 6. Vehicle Operating Cost Model and User Guide

6.1 Vcost Model Development

The development of the Vehicle Operating Cost (Vcost) model depended on several main segments. Most importantly the representative set of vehicle classes needed to be defined. As noted in Chapter 3, this was created from reviewing the current registered Texas fleet (light duty), coupled with analysis of Weigh-in-Motion (WIM) data, to obtain heavy-duty fleet configurations. This was also supplemented through a series of interviews that the research team undertook with heavy-duty fleet operators throughout Texas to get a sense of "what is on the ground." This composition was then weighted relative to the number of vehicles in each class and, from this, a set of representative vehicles was derived. These can be seen in Table 6.1.

Table 6.1: Representative Vehicle Fleet Utilized in Vcost Model

CARS AND LIGHT-DUTY TRUCKS			
CLASS CARS (Sedans & station wagons)	VEHICLES CHOSEN AS REPRESENTATIVE		
Subcompact			
Compact	Ford Focus	Honda Civic	Toyota Corolla
Mid-Size	Honda Accord	Nissan Altima	Toyota Camry
Large	Chevrolet Impala	Ford Taurus	Hyundai Sonata
Pick-up Trucks			
Small	Toyota Tacoma	Ford Ranger	Chevrolet Colorado
Standard	Dodge Ram 1500	Ford F100	Chevrolet Silverado 1500
Minivans	< 2% of Texas Fleet		
Vans	< 2% of Texas Fleet		
SUVs and Crossovers			
Small	Ford Escape	Jeep Liberty	Honda CRV
Mid-size	Jeep Grand Cherokee	Ford Explorer	Chevy Trailblazer
Large	Chevrolet Tahoe	Ford Expedition	GMC Yukon

Finally, the operating costs were researched and evaluated for each vehicle class. Trade data, academic research, and survey data was used to produce a set of costs for the light-duty and heavy-duty fleets.

6.1.1 Model Medium-Choice and Rationale

The alpha versions of the LDV and HDV models were initially created in spreadsheet form. It quickly became clear, however, that a spreadsheet could not present a clear, legible, easy-to-use, and modifiable model of sufficient complexity and depth.

A review of similar spreadsheet-based models revealed that all but the simplest models soon became confusing to the user when navigating through multiple worksheet tabs of formulae and data. The inherent structure of the spreadsheet yields a limited ability to guide the user through the process of utilizing the data and producing output. This design results in a steep learning curve for those who wish to use the model with the concurrent danger that the model will not be used.

Also, even with some read-only protection in place, there is concern that data or formulae can inadvertently be over-written by the user, which would render the model inoperable for a user. There was also concern that compatibility issues between different versions of a spreadsheet program could lead to corruption of the Vcost model, or other complications in its operation.

Our research team then reviewed different media to find the appropriate model and language with which to develop the Vcost model.

A form-based windows program was chosen because it can lead a user through the operation of the model with minimal complexity and yet still provide enough flexibility necessary to update the model as newer or more pertinent information becomes available.

There is a minor drawback to this medium. This is, if there are major, structural changes required to be made to the program, it does require a user with knowledge of programming. To avert this problem, almost all variables used in the operating costs model are editable by the user, which reduces the potential that reprogramming will be necessary. This also allows the program to be flexible and responsive to changes in the transportation landscape, such as changing fleet economics or conditions, fuel prices and gasoline taxes, and to be portable to a variety of differing conditions.

This medium for the Vcost spreadsheet manifests as an executable program (.EXE file). It is written in the Visual C# language. This does not require any additional software (other than the program itself) to be installed on the user's computer.

Six main cost categories were identified for vehicles: depreciation, financing, insurance, other fixed costs, repair and maintenance, and fuel. These costs fall into two categories: fixed and variable costs. This section will describe how these costs, and the method by which they are approximated in the model, were developed.

6.1.2 Vehicle Age

Costs associated with vehicle operation vary strongly with vehicle age. Interestingly, the national median car age is 9.4 years, and the Texas average car age is 7.5 years. Most vehicle operating cost studies only examine the first 4 years of vehicle life. Because light vehicles' ages average around 7 years in Texas, and because the average vehicle finance term is 5 years, the research team decided to estimate costs up to 20 years of vehicle age. In the Vcost model, each cost associated with the representative vehicle was calculated for each year of operation up to 20 years. The operating costs associated with that vehicle are taken from a weighted average of those 20 years, where the weighting per year was developed from the analysis of VTR data.

Because much of the research and knowledge pertaining to the cost of heavy-duty trucks is proprietary, most of our data and information used to calibrate the Vcost model came from our survey sources, with some assistance from trade publications and academic media.

6.1.3 Depreciation

For LDVs, numerous sources in the literature were reviewed to gather information. What was found was that vehicle depreciation is usually modeled as a fixed percentage per year, typically 20%. Because vehicles are known to depreciate more in the first year of ownership than in subsequent years, a more refined model of depreciation was attained by using different values for depreciation in the first year than for subsequent years. The values for both first year and subsequent yearly depreciation can be edited by the user in the Inputs window. The new car value for a representative vehicle can be edited in the Representative Vehicle Inputs window; this will affect the depreciation cost associated with that vehicle.

For HDVs, the average vehicle yearly utilization, lifespan, and years of life were found from the HDMA's 2007 study *Heavy Duty Truck Maintenance in the USA Volume 9* as well as from our survey sources.

6.1.4 Finance

The research team then reviewed financing options for vehicle purchases. Our studies revealed that approximately two-thirds of new vehicle purchases are financed. The cost of financing is dependent on the cost of the new vehicle, the interest rate, the down payment amount, the term of the loan, and the credit score of the individual or group financing the vehicle.

The National Automobile Dealers Association (NADA) produces a yearly publication of statistics relating to car dealership sales. The 2008 NADA Data publication provided quarterly information regarding the average financing rate and average loan length from years 2001-2007. The default finance rate and loan term (length) were chosen based on the averages over the last 5 years of data, and were 4.53% and 61 months, respectively. Leased vehicles were not taken into account because it is a smaller percentage of the total market share.

Finance parameters, such as the percentage of new car purchases that are financed, the average interest rate, the average down payment, and the average load term can be changed by the user in the Inputs window of the Vcost model.

For HDVs, information concerning financing costs was found from the OOIDA's survey of owner-operators and from industry survey.

6.1.5 Insurance

Insurance rates were also calculated for the LDV and HDV fleets.

For light-duty vehicles, this is the average amount paid yearly for vehicle insurance. Vehicle insurance is much more dependent upon the driver than on the vehicle. While the nature and value of the vehicle may have some effect on the yearly price of insurance (for example, a Miata may cost more to insure than an Odyssey) the driver's characteristics, such as age, location, driving history, and credit score, play a much greater role. There is also variation in insurance costs based on the driver's choice of comprehensive insurance rather than just liability insurance. For these reasons, insurance cost was not analyzed specifically for each representative vehicle. Instead, the average amount paid for insurance was used. A study by the Insurance Information Institute (www.iii.org) revealed that Texans paid on average $880 for vehicular insurance in 2004.

For heavy-duty vehicles, the average yearly insurance cost was found via survey data. Again this value can be edited by the user in the Inputs window of the Vcost model.

6.1.6 Repair

The per-mile cost of light-duty vehicle repair has been shown to follow a linear trend with vehicle use in miles.

Consumer Reports collects data on vehicle performance by model and age in its ongoing customer survey, the last of which included 1.4 million vehicles. This data was taken from the Consumer Reports data available in fall 2008 to its subscriber base. They use this survey to estimate owner costs for a vehicle, for which “maintenance and repair” is a category. Consumer Reports generated the cumulative maintenance/repair for the 1^{st}, 3^{rd}, 5^{th}, and 8^{th} year of ownership (the mileage per year was given). From these values, a linear trend was derived and used to calculate the repair cost per mile as a function vehicle age in miles.

Obviously, repairs are affected by the vehicle age and the utilization. The utilization can be altered in the Inputs window of the Vcost model.

The repair parameters of a particular vehicle, represented as the slope (m) and intercept (b) values describing the line that gives the dollar-per-mile repair cost versus the miles-driven, is editable by the user in the Representative Vehicle Inputs window.

The cost of repair for heavy-duty vehicles was found from the HDMA’s 2007 study *Heavy Duty Truck Maintenance in the USA Volume 9.* Data that was collected from surveys was also used in this calculation. The average per-mile maintenance cost for a FHWA Class 9 truck was $0.1439 for a private fleet and $0.1603 for owner-operators.

6.1.7 Fuel

The Fleet Output window allows the user to compare fuel cost for free flow, moderate congestion, and heavy congestion. The fuel use for any of these vehicles can be examined in greater detail in the Fuel Efficiency Model.

The fuel cost is greatly dependent on the price of gasoline and diesel fuel. These prices can be set by the user in the Inputs window.

6.2 Vcost Model Review

The Vcost model provides operating costs estimates for the user for specific representative vehicles as well as fleets of vehicles. The model allows the user to change key parameters so that the cost calculation is specific to any particular situation the user wishes to model, and can be updated as the economic or technological landscape changes.

The model looks like a typical Windows environment program. The user has buttons that are clicked with the mouse to move forward in the program, as well as go back to previous pages. As the user moves the mouse over the screen elements, ‘tooltip’ boxes appear that describe input values and variables to guide the user through the program. This view was deliberately chosen by the research team to provide the user with a program that looked, felt, and operated in a similar fashion to most Windows programs and would be intuitive for the user.

A screen shot of the opening program can be seen in Figure 6.1.

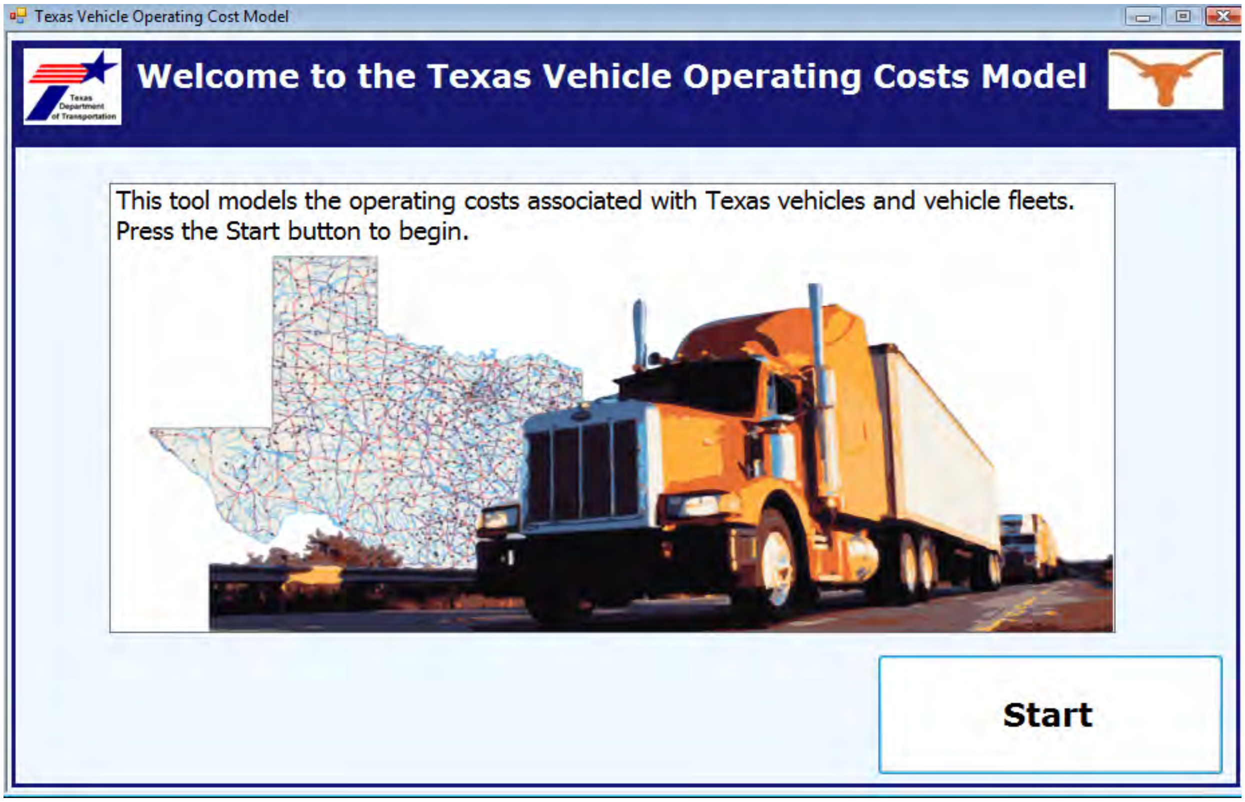


Figure 6.1: Opening Screen of Vcost Model

6.2.1 Program Flow

The program begins at the **Main** window (Figure 6.1). By clicking the "Start" button, the program then guides the user through menus and opportunities to alter program parameters until he arrives at an output form. This form displays the resulting operating costs, including a graphical breakdown of each cost as a percentage of total costs. At any point in this process, the user can return to the **Main** window by clicking "**Quit**." This output can also be printed.

After the **Main** window, the first page the user sees is the **Parameter Menu** window, which is labeled "Inputs" and can be seen in Figure 6.2. In this window, the user is able to change parameters relating to the economic climate as a whole, for example, fuel prices or interest rates. This does not involve parameters related to a specific vehicle or vehicle class or fleet composition; that is presented to the user in a later screen.

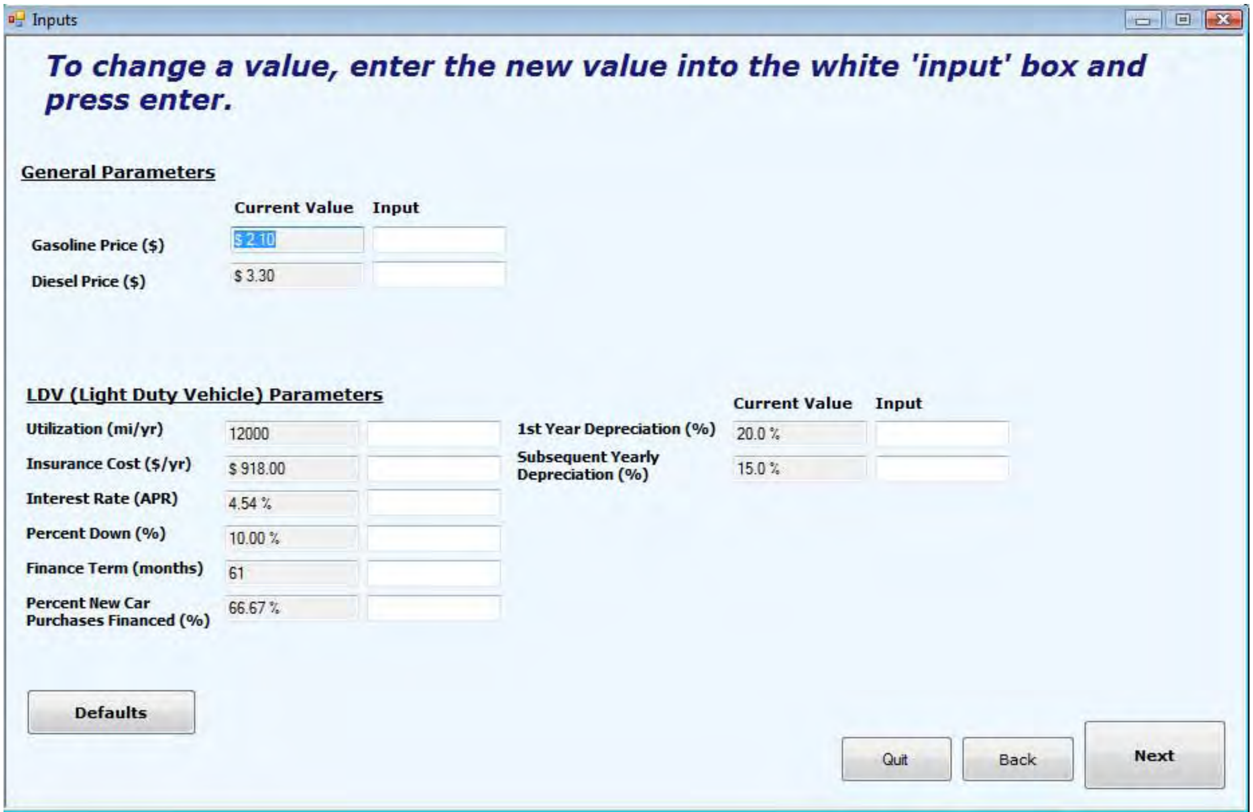


Figure 6.2: Vcost Model Parameters (Inputs) Main Menu

Clicking “**Next**” presents the user with the choice to examine the output for a representative vehicle or representative vehicle class, or look at fleet output. This can be seen in Figure 6.3. The first option allows the user to look at just a representative vehicle class, such as mid-sized cars, or just a representative vehicle, such as a Honda Accord. The second option examines the average per-vehicle operational cost of a fleet of vehicles, where the fleet can either be the default Texas fleet or a user-specified fleet.

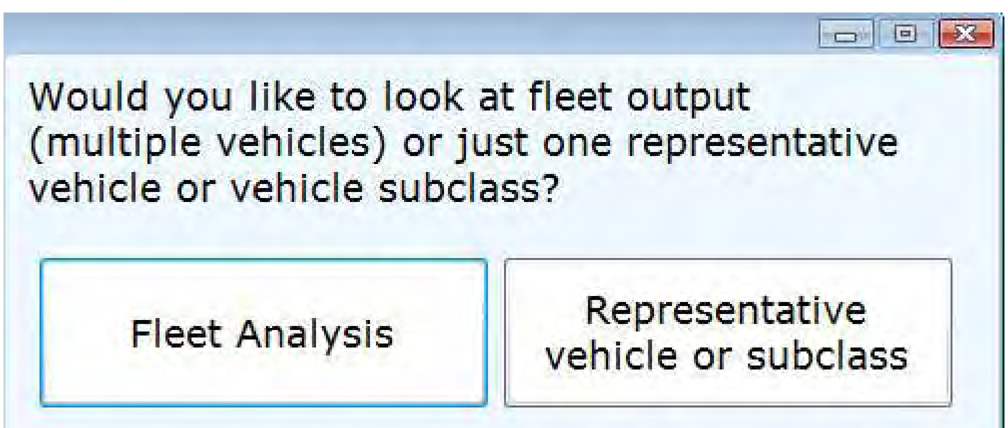


Figure 6.3: Menu to Chose Fleet or Representative Vehicle Output

If the user chose the first menu option ("representative vehicle or class"), the user will be presented with the **Representative Vehicle Menu** window (Figure 6.4).

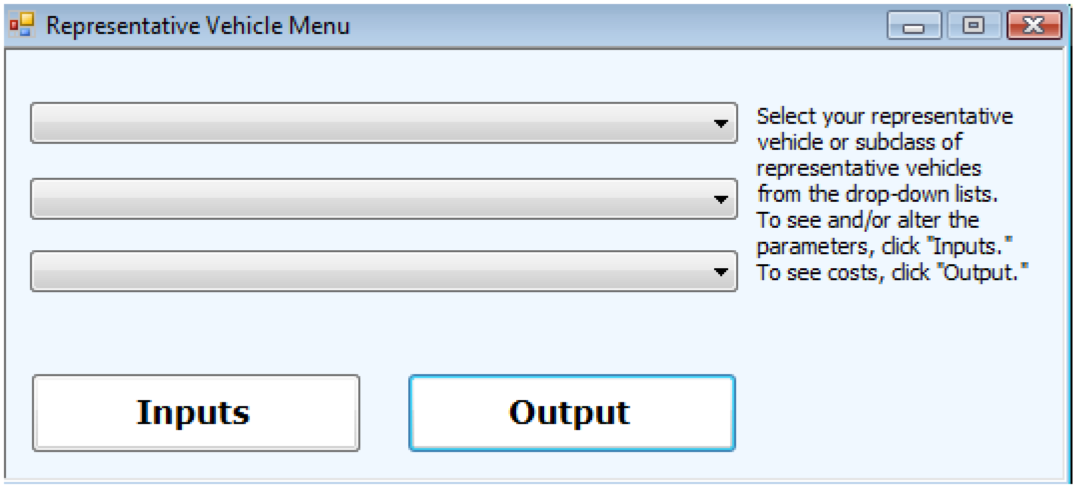


Figure 6.4: Representative Vehicle Menu

This window contains three drop-down lists by which the user can specify the representative vehicle or class of interest. Figure 6.5 shows a selection of a car that is compact and is a Honda Civic.

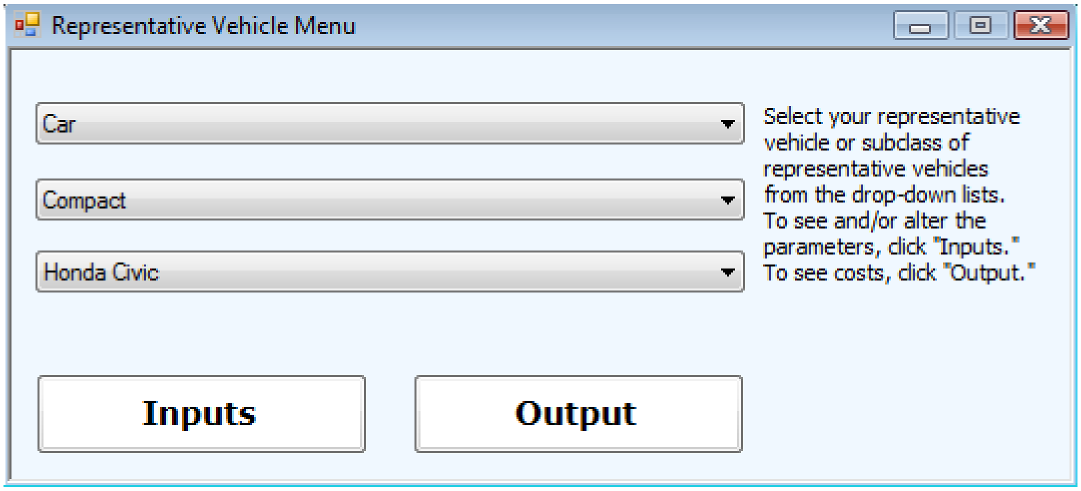


Figure 6.5: Representative Vehicle Menu Selection

The **Inputs** button opens the **Representative Vehicle Parameters** window, which allows the user to view and change parameters related to the selected representative vehicle or class. The screen that the user will be presented with can be seen in Figure 6.6.

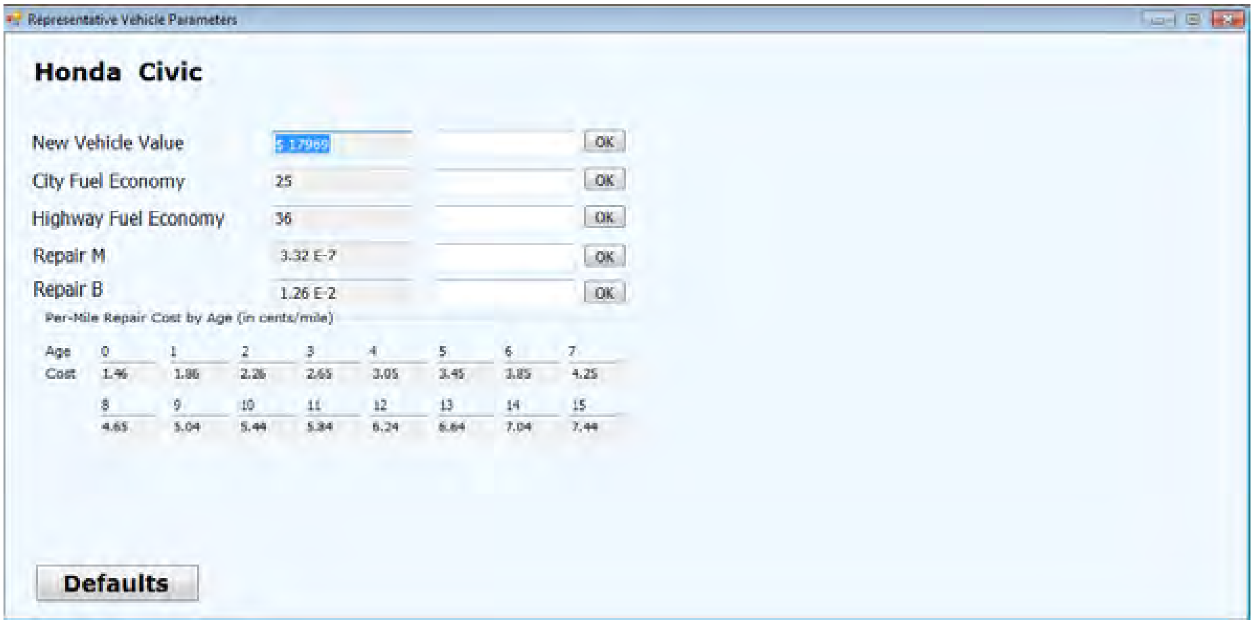


Figure 6.6: Representative Vehicle Parameters

The **Representative Vehicle Parameters** window allows the user to view and change parameters relating to a specific representative vehicle or vehicle subclass. As can be seen the user can change the vehicle value, fuel economy, and repair components by entering in new data in the white boxes and clicking OK.

The **Representative Vehicle Output** window displays the operating costs associated with the selected representative vehicle or vehicle class. For each vehicle and vehicle class, costs are calculated for vehicles aged from 1-20 years. The default display is a weighted average that represents a typical age distribution of vehicles. The user may select any age and view the cost associated with that age of vehicle. Figure 6.7 shows output per mile for the Honda civic at year 2 of age.

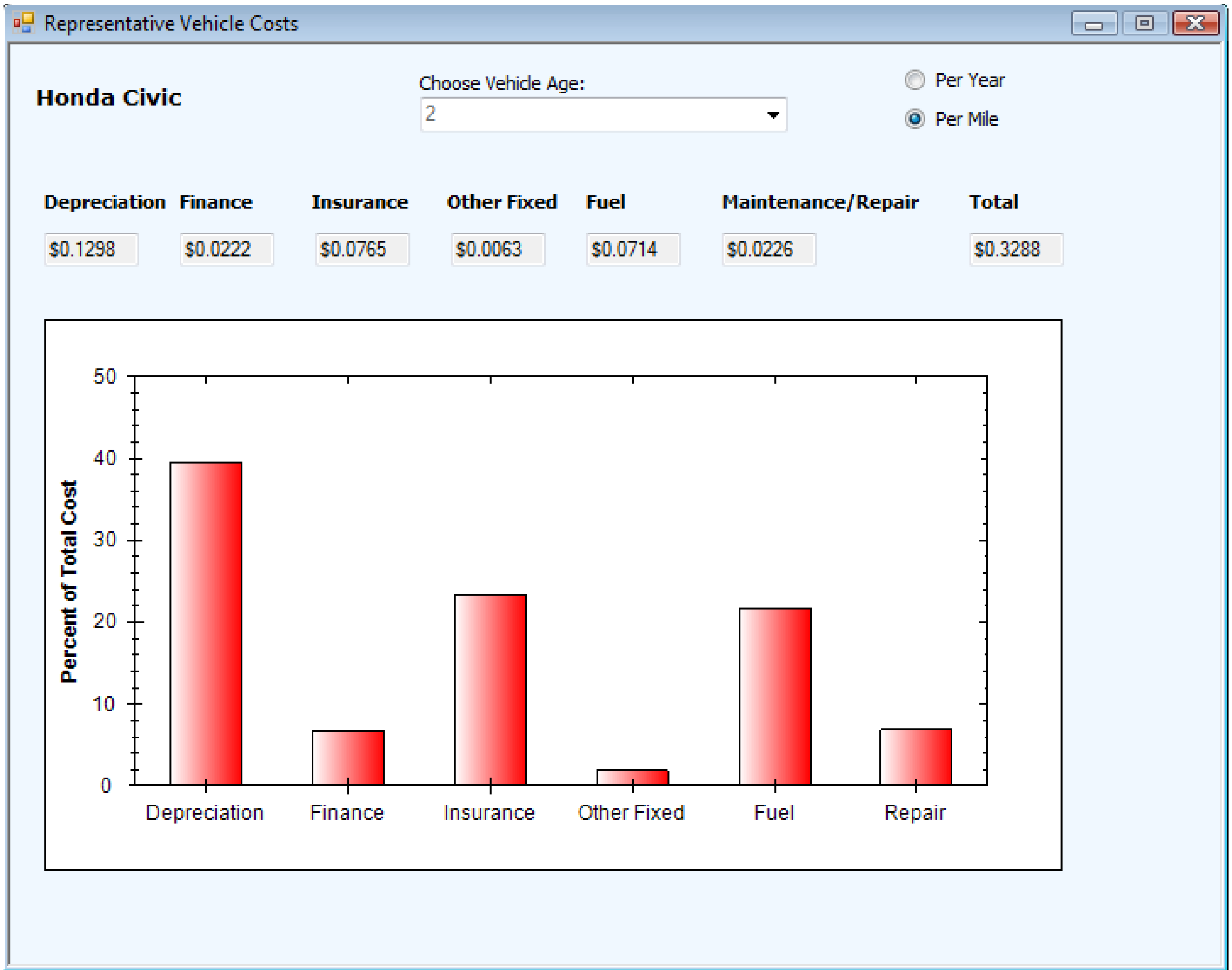


Figure 6.7: Output from Representative Vehicle Inputs

The **Output** button opens the **Representative Vehicle Output** window where the operational costs are displayed for the selected representative vehicle or vehicle class. The default shows the vehicle age as a weighted average and will display the per year costs. This can be seen in Figure 6.8.

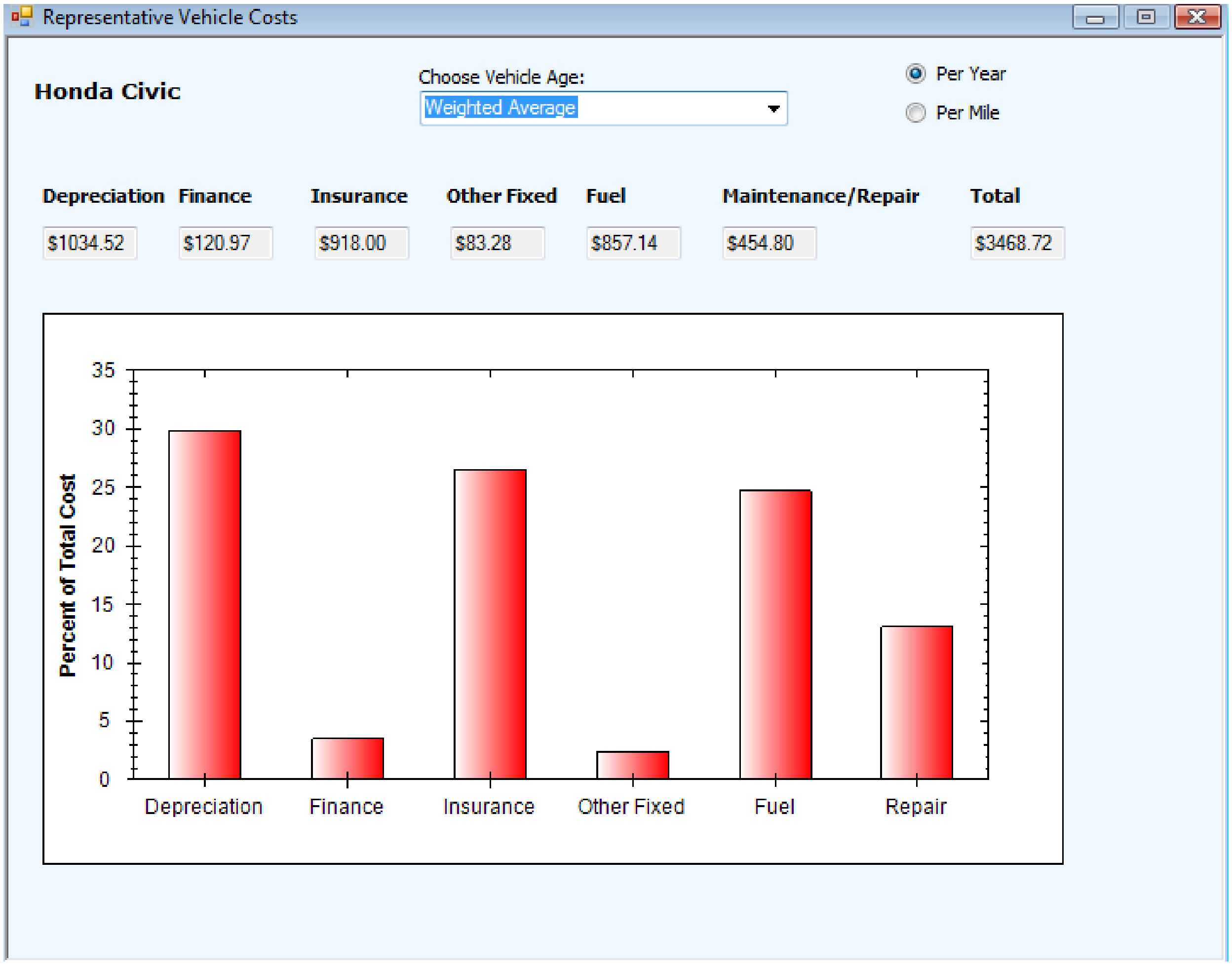


Figure 6.8: Main Output Screen from Representative Vehicle Selection

If the user chose the second menu option ("fleet of vehicles"), the user will be presented with the **Fleet Composition** window, which will present the default fleet composition. The user can choose to change the fleet composition by entering a new composition and clicking "**OK**." The fleet composition window can be seen in Figure 6.9.

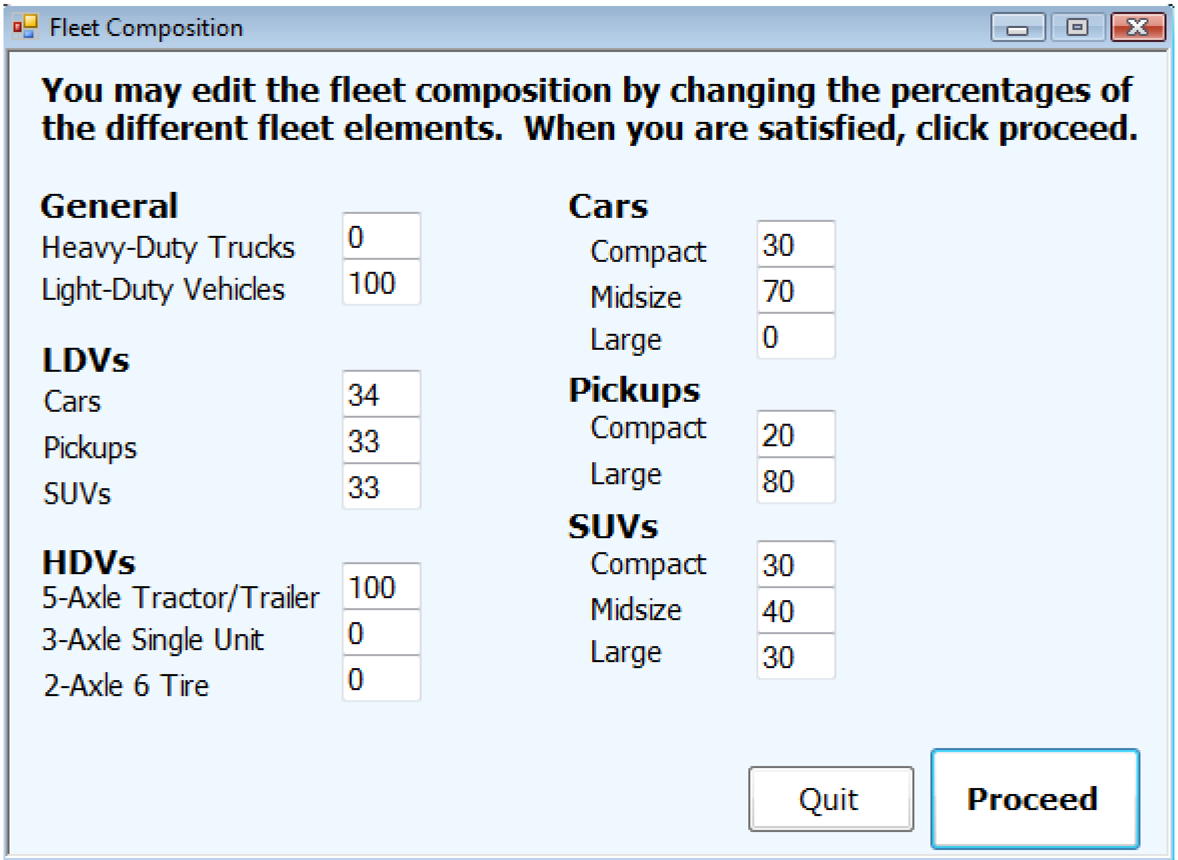


Figure 6.9: Fleet Composition Window

The fleet composition is represented by the percentage of each vehicle class in each category; these percentages are shown in the white boxes by each category name. Note that these entries are *not* the absolute number of vehicles in each category. For example, a fleet is composed of 13% HDVs and 87% LDVs. Of the LDVs, 40% are sedans, 30% are pickups, and 30% are SUVs. Of the sedans, 25% are compact, 45% are mid-size, and 30% are large.

Once an acceptable fleet composition has been made, the user clicks "**OK"** to proceed to the **Fleet Output** window. This can be seen in Figure 6.10. The **Fleet Output Window** displays the operating costs associated with the fleet of vehicles chosen. It represents the average operating cost for one vehicle of the fleet. This is found by taking a weighted average of the costs associated with each representative vehicle class. To get the total operating cost of the fleet, the user can multiply the results by the number of cars in the modeled fleet. The results can be shown either per year or per mile, and the user has the option to pick a traffic condition that they wish to view. There are three traffic conditions currently modeled: free flow, moderate congestion, and heavy congestion.

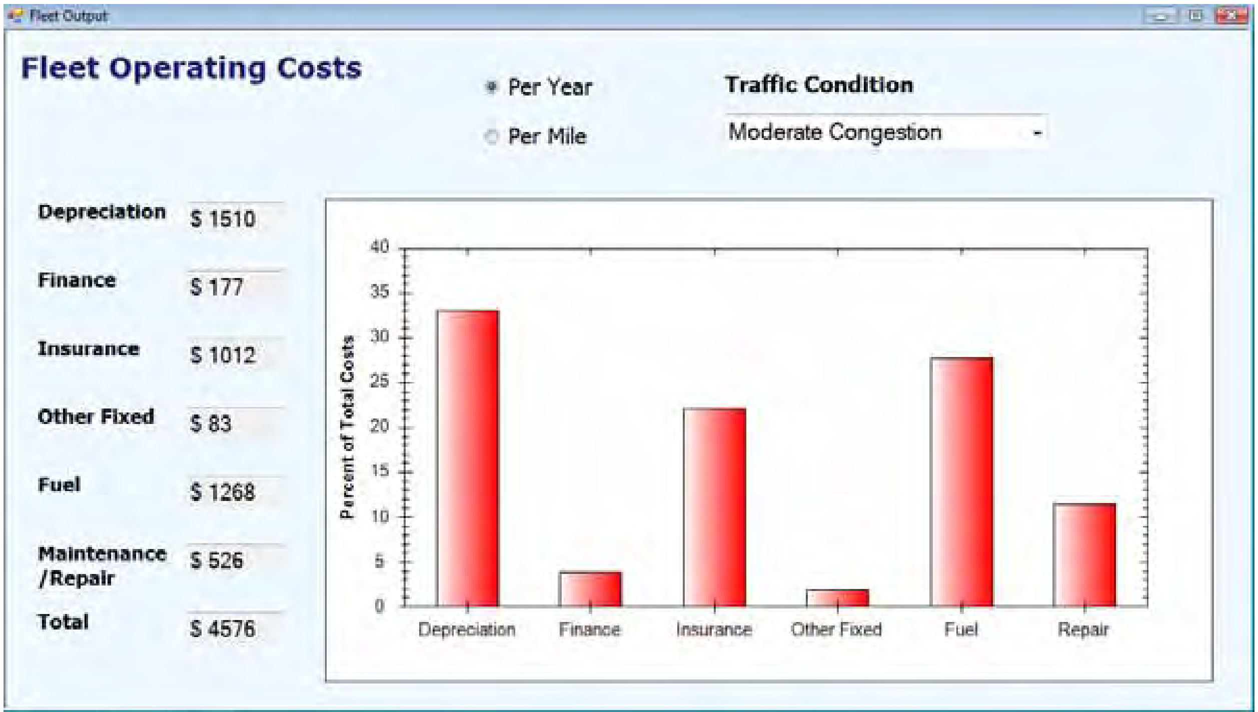


Figure 6.10: Fleet Output Window

6.3 Summary

This chapter summarized the basic program flow for the Vcost model. It enables a user to understand the program, the basic data for determining the relationships reported in the output, and how Vcost estimates can be made for future Texas fleet compositions. Further refinements are planned for the basic model following testing within TxDOT Divisions and incorporating new enhancements to estimate fuel consumption of a variety of hybrid vehicles forecasted to be in use within the next decade. A summary of the project is presented in the next and final chapter, together with recommendations for further improvements to the Vcost model.

Chapter 7. Summary and Recommendations

7.1 Summary

Key events in the areas of input cost, new technologies, and legislative requirements have significantly impacted vehicle ownership in Texas over the past decade. These, however, are not captured by current cost estimation routines used by planners and economists. As an example, the most widely used Texas vehicle operating cost (Vcost) model dates back one-quarter of a century. Relationships in the model do not reflect recent vehicle engine and transmission improvements, changes in operations and VMT due to fuel costs, new fuel types, and the benefits of both vehicle aerodynamics and tire characteristics. Simultaneously, legislative mandates in the U.S. have had significant impacts on fuel efficiency and consumer choice. Therefore, the goal of TxDOT Project 0-5974 was to develop a basic up-to-date vehicle operating costs model reflecting Texas conditions.

The first task was to evaluate relevant Vcost literature, particularly that developed for established countries or regions. Historically, Vcost research in the planning area has focused on developing countries where wide ranges of pavement designs are encountered, together with extreme differences in pavement conditions, especially roughness. Two significant models dominate the body of work, the first developed by World Bank sponsorship (Highway Design and Maintenance model—HDM III) in 1988 and an updated version sponsored by the Asian Development Bank (Highway Development and Management system—HDM IV) released a decade later. In 2006 a U.S.-sponsored Vcost study, NCHRP 01-45 began ahead of the TxDOT 0-5974 work and apparently recommended at the end of Phase 1 that the Vcost model should be a calibrated version of the HDM IV pavement condition—Vcost model. This was somewhat surprising because HDM IV covers a range of vehicles that include non-motorized types, attempts to estimate issues beyond Vcost and only changes the fuel estimation sub-model of the auto and truck classes developed in HDM III[14]. Succinctly, both HDM III and IV work best in countries with wide ranges of pavement condition, weak maintenance systems, and macro-economic conditions different from those in the U.S.

The CTR research team decided to develop a specific Vcost model for Texas conditions. This decision was based on of the research team's ability to develop a sophisticated fuel model for light-duty vehicles, several excellent sources of secondary vehicle data, and the capability to measure heavy truck fuel consumption through both experimental and survey work. The basic model was first designed to address the relatively narrow range of pavement roughness found on most of the Texas highway network and would be free-flow, in that it does not accurately measure congestion effects. That decision was built on a preference to use resources to measure the light-duty fleet—which constitutes over 10 million registered vehicles—more precisely to ensure better estimates of fuel consumption and state DOT revenue streams. The complexity of capturing congestion accurately within the boundaries of the study resources also had an effect.

The second task centered on how to classify the variety of vehicles that travel Texas' roadways. Many classification schemes are available, including those from the EPA, FHWA, and

[14] NCHRP 01-45 "Pavement Conditions on Vehicle Operating Costs" is in the second study phase and has yet to report any results, so the 0-5974 authors are unable to make direct comparisons between the two bodies of work. They are, however, very familiar with both the HDM III and IV models.

Texas 6. Each of these was found to have advantages and disadvantages, and none were considered sufficient for the study purposes. Therefore, the team developed a classification scheme that should be more suitable for TxDOT planning and revenue forecasting. The following three data sources were used to generate the selected classification.

- Vehicle Title and Revenue Data[15]
- Weigh-in-Motion Data and Vehicle Counts (traffic survey data) from TxDOT
- Automotive News[16] Sales History for years 2002 through 2008

These resources led to the adoption of eight categories of light-duty vehicles (<8,500 lb GVWR but also including vehicles intended to transport people with a GVWR up to 10,000 lb) comprising 3 classes of cars and station wagons (compact, mid-size, and large), 2 classes of light-duty pickups (small and large), and 3 classes of SUVs (small, mid-size, and large). FHWA's classifications for heavy-duty trucks were used because they match the data derived from both TxDOT weigh-in-motion sites and published traffic survey reports. In addition, these classes correlate with the EPA classes and assist in air quality assessments.

Specific vehicles were then chosen within each class to "represent" the typical characteristics of each class. This technique is a long established research procedure going back to the fundamental Iowa work undertaken in the 1930s as a broad planning model cannot exactly replicate the subtle technical variations present within each class. This is particularly true in the light-duty class, which covers a numerous and widely different category in Texas. Even so, emphasis was given to this category. In the $15 million HDM III study, four light-duty categories were studied, a number that was doubled in this study. The operating costs for the representative vehicles were then calculated and averaged to provide the overall operational cost for this specific class.

The current Texas fleet composition was determined from 2007 VTR data and made a default for model use if current fleet impacts were needed. However, the model user can alter input values to reflect reported or estimated changes in future fleet composition. Most vehicle operating cost models examine the first 4 years of vehicle life. The team found that light-duty vehicle age averaged around 7 years in Texas, and because the average vehicle finance term is 5 years, each cost associated with the representative vehicle was calculated for each year of operation up to 20 years in the present study Vcost model. Six main cost categories were included in the Vcost model: depreciation, financing, insurance, other fixed costs, repair and maintenance, and fuel. These costs fall into two categories: fixed and variable costs.

The Vcost model provides operating cost estimates for specific representative vehicles as well as fleets of vehicles. The model allows the user to change key parameters so that the cost calculation is specific to any particular situation the user wishes to model, and can be updated as the economic or technological landscape changes. The model looks like a typical Windows environment program. The user has buttons that are clicked with the mouse to move forward in the program, as well as go back to previous screens. As the user moves the mouse over the screen elements, 'tooltip' boxes appear that describe input values and variables to guide the user through the program. This view was deliberately chosen by the research team to provide the user

[15] Vehicle Title and Revenue activities were a TxDOT Division when the study was carried out but during the last state legislative session they were made a separate state agency.
[16] Automotive News is an excellent source of industry information: http://www.autonews.com/section/datacenter.

with a program that looked, felt, and operated in a similar fashion to most Windows programs and would be intuitive for the TxDOT user.

This model not only provides estimated operating costs for various vehicles, but also calculates the average per-vehicle cost for a user-defined fleet. The fleet composition in the model is defined by the percentages of each of its constitutive vehicle classes and subclasses. For example, a fleet may be defined as a percentage of heavy trucks and light-duty vehicles. The light vehicles may then be further defined as another set of percentages of cars, light-duty pickups, and SUVs. This sub-category can also be sub-categorized into two or three further subclasses (e.g., compact cars, mid-size cars, and large cars). A default case, representing Texas vehicular traffic in aggregate, is also available. This functionality was also created and developed to allow the TxDOT user to tailor the model to the different fleet compositions and produce different outputs to guide policy makers and financial decision makers within TxDOT, the MPOs, and RMAs. As an example, the model could be useful in understanding the effects of the recent “Cash for Clunkers” program on fuel efficiency, costs, and potential gas tax revenues.

The fuel cost model incorporated within our Vcost model is “class-specific.” Vehicle sales records were used to identify the three or four vehicles within each class that represented the major share of sales within that class of vehicle. The city, highway, and composite fuel economy averaged over these three or four vehicles are estimates for the fuel economy for that class of vehicle during arterial, free flow highway, and congested highway operations. A separate, stand alone, “vehicle-specific” fuel economy model was also developed. This fuel economy model provides the user with the city and highway fuel economy, the overall drivetrain efficiency during each type of operation, and the fuel cost per 100 miles of operation. This fuel economy model currently has a data base of more than 1,200 vehicles produced during model years 2003–2008. The user of this stand alone fuel economy model can also examine the fuel economy of any of these vehicles as a function of cruising speed.

7.2 Recommendations

The Vcost model should now be tested within TxDOT with a variety of staff to facilitate both final testing and iterative improvements to the basic model provided as the Product of this work. The dynamic nature of vehicular design and the adoption of new technologies require further work to enhance the model so that it can be used over the next decade. Accordingly the research team recommends the following activities be undertaken over the next 2 years:

1. Include at least three levels of congestion, to be determined from TxDOT staff interviews, to allow the Vcost model to predict the increases in the per mile cost for each congestion levels.

2. Evaluate whether a regional dimension to the basic Texas Vcost calculations can be added to the model. Tire costs are higher in some areas of the state and if other cost differentials are noted by vehicle operators, further discrimination could be built into the model.

3. The heavy truck portion of the Vcost model centers on the 5-axle, 18-wheel semi-trailer truck because it dominates the state’s heavy truck VMT. It is recommended that a 3-axle rigid truck (as with the smaller “dump” truck) be added and that the potential for building a “made to order” heavy truck design based on attributes. The

user would select an engine and transmission, axle numbers, vehicle weight, and other basic information and the model would calculate the cost per mile. The interest in this approach will be determined as part of the model testing within the Department.

4. In 2010, the final U.S. Environmental Protection Agency (EPA) truck engine requirements of the current decade for improving exhaust emissions will come into force. Already one engine manufacturer—Caterpillar—is withdrawing from the heavy truck engine market and two different technologies are being implemented to meet the stringent conditions. One concentrates on engine combustion and exhaust gas recirculation (EGR, a simple description of an extremely complex activity)[17] while the other requires urea to be injected into the vehicles' exhaust stream to "scrub" the oxides of nitrogen (NOx) from the diesel exhaust. The system, termed "urea-based selective catalytic reduction" or SCR is believed by many to be the only technology available that can remove enough NOx from diesel exhaust to comply with strict new limits imposed by the EPA[18]. Clearly Navistar beg to differ and are counting that if they can make EGR work, the weight advantages over SCR will make it competitive. Consumption of the urea solution[19] is about 3% of the diesel consumption and if diesel trucks average 6.5 miles per gallon (2.8 km/liter), an average diesel truck will need to refill its 20-gallon tank of urea every 4,000 to 6,000 miles (76 liters every 6,400 to 9,600 km). Twenty gallons of DEF will weigh around 107 lbs, excluding the tank, piping, and monitoring device in the exhaust system. Further work would capture the impacts of the EPA requirement and keep the cost estimates up to date.

5. Truck manufacturers are beginning to evaluate hybrid technologies being developed by transmission companies in an effort to reduce fuel consumption and exhaust emissions. Coca-Cola is testing over 100 delivery trucks, many in Texas, with a system developed by Eaton Corporation, that will lower engine power. Improving the Vcost sub-models for the differential, transmission, and engine to capture these recent technological advances is highly desirable.

6. Finally, the light-duty auto and pick-up class is likely to incorporate several different “hybrid” technologies that would enable the Vcost model to be used over the next decade. At the outset of this work, mention was made of the two major contributions the results could make to TxDOT operations, namely economic engineering evaluations of different types and revenue estimation from fuel consumed in the state. The basic model reported as the product of this work should be enhanced to allow its utility as vehicle, engine, and transmission designs continue to evolve in the period 2010–2020.

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[17] MaxxForce, a technology developed by Navistar; see Transportation Topics Webinar, October 19 2009.

[18] Glenn Kedzie, Environmental Counsel for the American Trucking Associations quoted in http://www.eurekalert.org/pub_releases/2008-11/i-uto111008.php.

[19] The urea is in solution, technically a 32.5% nitrogen solution of demineralized water termed “diesel exhaust fluid” or DEF. It has a similar weight to water with reduced potential vehicle productivity.

7.3 Phase Two of the Vcost Study

In August 2009, TxDOT staff decided to extend the Vcost research an additional 2 years to address several issues that would allow the model to be used over the coming decade. The following modifications and improvements will be incorporated into the mechanistic structure of the model to capture the new technologies being developed and implemented by vehicle manufacturers.

Transmission sub-model

a) The sub-model for the performance and efficiency of a manual transmission incorporated within the basic vehicle-specific fuel economy model as of the end of FY 2009 will be expanded to more accurately represent manual transmissions in light-duty and heavy-duty vehicles and also to represent "semi-automatic" transmissions (automatically shifted manual transmissions).

b) The approximation used in the model at the end of FY 2009 for the performance and efficiency of an automatic transmission will be replaced by an accurate, physically-based sub-model that is suitable for both a conventional automatic transmission and an automatic transmission with a lock-up torque converter.

Differential sub-model

c) The FY 2009 sub-model for the differential will be updated and expanded to more accurately reflect the performance and efficiency of modern differentials used in both light-duty and heavy-duty vehicles.

Engine sub-models

d) The FY 2009 sub-model for the performance and efficiency of a spark ignition engine will be replaced with UT's award-winning Fractal Engine Simulation (FES) model and a more accurate sub-model for the frictional, viscometric, and viscometric losses in the engine will be developed and incorporated in the vehicle-specific fuel economy model.

e) The FY 2009 sub-model for the performance and efficiency of a diesel engine, which is accurate only for diesels that met heavy-duty emissions standards prior to calendar year 2007 will be augmented by a diesel engine that is accurate for the more recent years and will be developed by the UT research team

Drivetrain sub-model

The FY 2009 vehicle-specific fuel efficiency model will be expanded to include fuel efficiency predictions for the conventional hybrids, mild hybrids, and hydraulic hybrids used in both light-duty and heavy-duty vehicles.

Alternative fuels

The FY 2009 vehicle-specific fuel efficiency model will be expanded to include the effects of biofuels (E85 and biodiesel blends) on fuel efficiency.

Drive cycle development

Standardized driving schedules will be developed for both light-duty vehicles and heavy-duty vehicles for travel on congested freeways and for free flow operation on freeways. Because travel on IH 35 through Austin during rush hour is believed to be representative of congested freeway operation in Texas, these driving patterns will be generated by car-following methods for both heavy-duty trucks and light-duty vehicles through Austin during rush hour traffic (congestion) and at times of the day when free flow operation is possible.

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Western Governor's Association—Clean and Diversified Energy Initiative

http://www.westgov.org/wga/initiatives/cdeac/index.htm

West Coast Governor's Global Warming Initiative

Powering the Plains

http://www.gpisd.net/index.asp?Type=B_BASIC&SEC={60AE7483-FD54-4D59-BE7D-B9560589263D}

http://www.gpisd.net/index.asp?Type=B_BASIC&SEC=%7B69A636DC-F9CD-4166-B21D-5BDD00DD4032%7D

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http://www.negc.org/links.html

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Southwest Climate Change initiative

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Appendix A: VTR QUERY MEMO

From: Rob Harrison

To: Don Lewis - TxDOT

Date: June 30, 2008

Re: VTR Database Query Items

Introduction/Summary

This is an explanation of the VTR data base pulls we request for our research for TxDOT on vehicle operating costs (Vcosts). We are using the data to get a representative view of what types of vehicles Texans own and in what proportion, so that we can develop a representative fleet operating on Texas roads.

We will be using this data in conjunction with traffic survey data such as Weigh-in-Motion (WIM). While WIM can give us data on the number of vehicles of different weights currently traveling on the roads, only VTR can provide information such as ages and makes of the vehicles, and differentiation of smaller vehicles into classes (compact sedans, midsize SUV's, etc). This information is essential to correctly estimating vehicle operating costs, as different sized vehicles have different costs (such as fuel consumption, for example.) Likewise, the costs of vehicles of different ages are much different; an older vehicle has much higher repair cost and typically higher fuel consumption, while it has a much lower depreciation cost and little-to-no finance cost.

In addition to predicting Vcosts for the current Texas fleet, this information will help with forecasting future scenarios: for example, what happens if the current trend of people trading in older trucks for new, compact cars continues, or what happens if hybrid adoption rises to 10% of the vehicle fleet. This will allow TxDOT to not just model the current situation, but flexibly respond to near- and long-term trends in transportation.

Listed below are our first requests for data pulls from the VTR database. The data can be in any format of spreadsheet or document that lists the requested data in columns- the example tables presented here are just for explanatory purposes.
Succinct statements of our query statements are put in bullet form and in maroon text for readability.

VTR Queries:

1) **Vehicle Age Distribution**
Knowing the age distribution of the vehicle fleet is necessary to calculating costs. We will adjust the age distribution by a utilization factor to account for lower usage of older cars.
   - Under the categories (**VEHCLASSCD**) of Passenger Car (**PASS**), we would like the number of vehicles currently registered for each model year, going back 20 years. We also, would like the total number of vehicles older than 20 years (not broken down into any categories just the total number).
   - Under the categories (**VEHCLASSCD**) of Passenger Truck (**PASS-TRK**), we would like the number of vehicles currently registered for each model year, going back 20 years. For the Passenger truck category, we'd like the passenger truck class further split along the PICKUP,SUV, and VAN designations outlined in Figure A2 (Appendix). Also, we would like the total number of vehicles older than 20 years (not broken down into any categories just the total number).
   Table 1 below shows an example of what this could look like.

Table A.1 Example table of data needed on model year distribution for passenger cars. We need a similar breakdown for passenger trucks

Passenger Cars

model year	<1988	1989	1990	1991	1992	1993	1994
# vehicles							
model year	1995	1996	1997	1998	1999	2000	2001
# vehicles							
model year	2002	2003	2004	2005	2006	2007	2008
# vehicles							

2) **Vehicle Class/Body/Year/(Make?)**
The cost of operating a vehicle depends not just on the year but also on the body class of vehicle: for example, a sedan has a lower overall operating cost than a sport-type small vehicle (like a convertible or coupe.) Likewise, pickups, minivans, and SUVs also differ. For this reason, the passenger car and passenger truck data is split up by body type (**VEHBDYTYPE**) (Figures A1, A2, and A3 in Appendix).

The vehicles within these categories are further subdivided by size: for example, a compact car such as the Yaris has a much lower operational expense and overall fuel consumption compared to a large sedan such as a Crown Victoria. There is no category know to us in the VTR database that differentiates on vehicles size classifications (compact, midsize, etc.) EPA classifications are assigned based on interior volume, which is not collected in the VTR database. We instead will differentiate roughly between vehicle size classifications by the weight of the vehicle. If necessary, we can convert this into gross weight by adding a weight value to represent passengers, their cargo, and a full fuel tank. Weight ranges have been determined for each vehicle size class (shown in table A2, Appendix).

This data could also be broken down by make if time permits this level of differentiation.

- Under the Passenger Car class type, we need the number of currently registered vehicles for each permutation of Body Type (Figure 1, Appendix), Weight Category (Table 2, Appendix), and Model Year.
- Under the Passenger Truck class type, we need the number of currently registered vehicles for each permutation of Body Type (Figure 2, Appendix), Weight Category (Table 2, Appendix), and Model Year.

Tables A2 and A3 below are an example of what this could look like.

Table A.2: Example table of data needed on Class/Body/Weight/Model Year breakdown for passenger cars

Passenger car			No. Vehicles Currently Registered						
			Model Year						
VTR Class Type	VTR Body Type	Weight Range	<1988	1988	1989	…	2006	2007	2008
Passenger car	SEDAN	Wc							
		Wm							
		Wl							
	SPORT	Wc							
		Wm							
		Wl							
	STATION WAGON	Wc							
		Wm							
		Wl							

Table A.3: Example of Class/Body/Weight/Model Year breakdown for passenger trucks

Passenger truck			No. Vehicles Currently Registered						
			Model Year						
VTR Class Type	VTR Body Type	Weight Range	<1988	1988	1989	…	2006	2007	2008
Passenger truck	PICKUP	Wct							
		Wlt							
	SUV	Wcs							
		Wms							
		Wls							
	VAN	Wcv							
		Wlv							

3) Vehicle Make

The makes we are interested in are outlined in Figure A4 (Appendix). Knowing the vehicle makes will allow us to approximate the % of luxury cars, which have a much higher operating cost. It will also allow us to adjust for make-specific trends, such as decreased maintenance or higher depreciation.

- For Passenger Cars, we wish to know the # of vehicles currently registered for each make.
- For Passenger Trucks, for each Body Type (PICKUP/SUV/VAN), we wish to know the # of vehicles currently registered for each make.

If time permits this information could be also broken up by model year.

Memo Appendix

Passenger Cars (PASS)	
SEDAN	
2D	2-Door Sedan
4D	4-Door Sedan
2H	2-Door Hatchback
4H	4-Door Hatchback
SD	3-Door Sedan/ 5-Door Sedan/ Notchback
HB	Hatchback/Liftback
STATION WAGON	
SW	Station Wagon
VT	Vanette
SPORT	
CP	Coupe
CV	Convertible
RD	Roadster

Figure A1: Body categories for passenger cars, by ***VEHBDYTYPE*** *code*

Passenger Trucks (PASS-TRK)	
PICKUPS	
PK	Pickup
SUV	
LL	Suburban/SUV
HB	Hatchback/Liftback
4H	4-Door Hatchback
VAN	
VN	Van/minivan
VT	Vanette

Figure A2: Body categories for passenger trucks, by ***VEHBDYTYPE*** *code*

Motorcycles & Mopeds (MTRCYCLE, MOPED)

2-WHEELERS

MC	Motorcycle
MD	Moped
MS	Motor scooter

*Figure A3: Body categories for motorized bikes, by **VEHBDYTYPE** code*

Table A4: Weight range descriptions (updated)

CURB WEIGHT (GROSS WEIGHT FOR PICKUPS)

	Weight range Description	minimum weight	maximum weight
Wc	Compact car	2200	3099
Wm	Midsize car	3100	3499
Wl	Large car	3500	4500
Wct	Compact truck (GVW)	<4499	4499
Wlt	Large truck (GVW)	4500	6500
Wcs	Midsize/Small Crossovers	3100	4299
Wms	Intermediate SUV	4300	5299
Wls	Large SUV	5300	6500
Wcv	Compact van (minivan)	<4999	4999
Wlv	Large Van (standard van)	5000	6500

Vehicle Makes (For passenger car and passenger truck categories)

Normal		# Cars
Buick	BUIC	
Chevrolet	CHEV	
Chrysler	CHRY	
Dodge	DODG	
Ford	FORD	
Geo	GEO	
GMC	GMC	
Honda	HOND	
Hummer (<2003)	AMGN	
Hyundai	HYUN	
Isuzu	ISU	
Jeep	JEEP	
Kia	KIA	
Mazda	MAZD	
Mini	MINI	
Mitsubishi	MITS	
Nissan	NISS	
Oldsmobile	OLDS	
Pontiac	PONT	
Saturn	STRN	
Scion	SCIO	
Subaru	SUBA	
Suzuki	SUZI	
Toyota	TOYT	
Volkswagen	VOLK	

Luxury/Near Luxury		# Cars
Acura	ACUR	
Audi	AUDI	
BMW	BMW	
Cadillac	CADI	
Hummer (2003+)	HUMM	
Infiniti	INFI	
Jaguar	JAGU	
Land Rover	LNDR	
Lincoln	LINC	
Mercedes-Benz	MERZ	
Mercury	MERC	
Porsche	PORS	
Saab?	SAA	
Volvo?	VOLV	

Other		#Cars
Any Other		

Figure A4: Vehicle Makes

Synopsis of VTR Database Queries:

1) Vehicle Age Distribution
    a. Passenger Cars
        i. Number vehicles currently registered for each model year category (MY less than 1988, MY is 1988, 1989, 1990, …., 2006, 2007, 2008)
    b. Passenger Trucks
        i. Body type (PICKUP/SUV/VAN)
            1. Number vehicles currently registered for each model year category (<1988, 1988, 1989, 1990, …., 2006, 2007, 2008)
2) Vehicle Body/ Class/Year (Also by make, if time permits)
    a. Passenger Cars
        i. Body Type (2d /4d Sedan, 2d/ 4D hatchback, Coupe, station wagon, 3D Sedan/5D Sedan/Notchback, etc.)
            1. Weight Class (compact, midsize, large)
                a. Model Year
    b. Passenger Trucks
        i. Body Type (Pickup, SUV/Suburban, …)
            1. Weight Class (compact, large)
                a. Model Year
3) Vehicle Make
    a. Passenger Cars
        i. Number Vehicles currently registered for each Make
    b. Passenger Trucks
        i. Body type (PICKUP/SUV/VAN)
            1. Number Vehicles currently registered for each Make

Appendix B: EPA Classifications

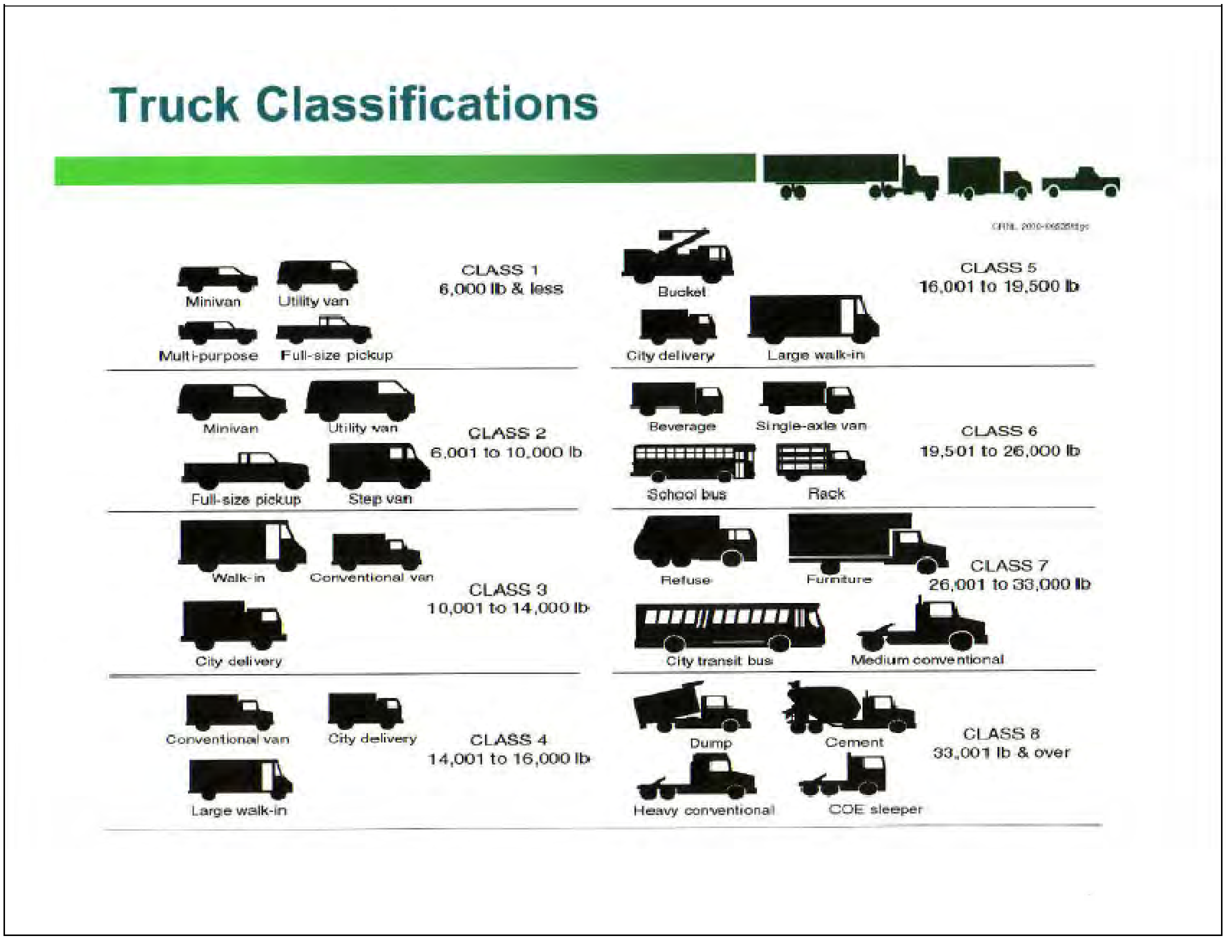


Figure B.1: EPA Classifications

VEHICLE WEIGHT DEFINITIONS

<table>
<tr><th colspan="2">Model Year</th><th colspan="6">GVWR (lbs)</th></tr>
<tr><th colspan="2"></th><th>6,000</th><th>8,500</th><th>14,000</th><th>19,500</th><th>33,000</th><th></th></tr>
<tr><td rowspan="2">Federal</td><td rowspan="2"></td><td colspan="2">LDT ≤ 8,500</td><td colspan="4">HDV > 8,500</td></tr>
<tr><td>LLDT ≤ 6,000</td><td>6,000 < HLDT ≤ 8,500</td><td colspan="2">8,500 < LHDDE < 19,500</td><td>19,500 ≤ MHDDE ≤ 33,000</td><td>HHDDE/Urban Bus > 33,000</td></tr>
<tr><td rowspan="7">California</td><td></td><td rowspan="7">LDT ≤ 6,000</td><td colspan="5">HDV > 6,000</td></tr>
<tr><td rowspan="2">1994 and earlier</td><td rowspan="2">6,000 < MDV ≤ 8,500</td><td colspan="2">8,500 < LHDDE < 19,500</td><td>19,500 ≤ MHDDE ≤ 33,000</td><td>HHDDE/Urban Bus > 33,000</td></tr>
<tr><td>8,500 < LHDE SI ≤ 14,000</td><td colspan="3">HHDE-SI > 14,000</td></tr>
<tr><td rowspan="2">1995+</td><td colspan="2" rowspan="2">6,000 < MDV ≤ 14,000</td><td>14,000 < LHDDE < 19,500</td><td>19,500 ≤ MHDDE ≤ 33,000</td><td>HHDDE/Urban Bus > 33,000</td></tr>
<tr><td colspan="3">HHDE-SI > 14,000</td></tr>
<tr><td>1992+ (LEVs, ULEVs, SULEVs, ZEVs only)</td><td colspan="2">6,000 < MDV ≤ 14,000</td><td colspan="3"></td></tr>
</table>

Figure B.2: EPA Emissions: Heavy-Duty Classifications

Acronyms and Abbreviations Used in This Guide

ABT	averaging, banking, and trading
cc	cubic centimeter
CFF	Clean-Fuel Fleet
CI	compression ignition
CO	carbon monoxide
EPA	U.S. Environmental Protection Agency
FR	Federal Register
g/bhp-hr	grams per brake horsepower-hour
g/km	grams per kilometer
g/kN	grams per kilonewton
g/kW-hr	grams per kilowatt-hour
gpm	grams per mile
g/test	grams per test
GVWR	gross vehicle weight rating
HC	hydrocarbons
HCHO	formaldehyde
HDE	heavy-duty engine
HDV	heavy-duty vehicle
HLDT	heavy light-duty truck
HHDDE	heavy heavy-duty diesel engine
HHDE	heavy heavy-duty engine
hp	horsepower
ICAO	International Civil Aviation Organization
ILEV	inherently low-emission vehicle
ISO	International Standards Organization
km	kilometer
kN	kilonewton
kW	kilowatt
lbs	pounds
LDT	light-duty truck
LHDE	light heavy-duty engine
LLDT	light light-duty truck
LEV	low-emission vehicle
LHDDE	light heavy-duty diesel engine
LPG	liquefied petroleum gas
m	meter
MDV	medium-duty vehicle
MHDDE	medium heavy-duty diesel engine
MW-hrs	megawatt-hours
NCP	nonconformance penalties
NMHC	nonmethane hydrocarbons
NOx	oxides of nitrogen
P	rated power of engine family in kilowatts
PM	particulate matter
r0	rated output
RPM	revolutions per minute
rPR	rated pressure ratio
SI	spark ignition
SN	smoke number
SULEV	super-ultra-low emission vehicle
THC	total hydrocarbons
THCE	total hydrocarbon equivalent
ULEV	ultra low-emission vehicle
ZEV	zero emission vehicle

Figure B.3: EPA Guide to Acronyms and Abbreviations

Light-Duty Car and Truck Classifications

Definitions of Vehicle Classifications:

LDV: All passenger cars

LDT1: Gross Vehicle Weight Rating (GVWR) 0-6000 lb
Loaded Vehicle Weight (LVW) 0-3750 lb

LDT2: GVWR 0-6000 lb
LVW 3751-5750 lb

LDT3: GVWR 6001-8500 lb
Adjusted Loaded Vehicle Weight (ALVW) 0-5750 lb

LDT4: GVWR 6001-8500 lb
ALVW 5751-8500 lb

Gross Vehicle Weight Rating (GVWR) is the value specified by the manufacturer as the maximum design loaded weight of a single vehicle

Loaded Vehicle Weight (LVW) is the vehicle curb weight plus 300 lbs: LVW=VCW+300 lbs

Vehicle Curb Weight (VCW) is the weight of the vehicle with all of its tanks full and components included but no passenger or luggage (load) adjustments (nothing in it).

Adjusted Loaded Vehicle Weight (ALVW) is the average of the vehicles GVWR and the Curb Weight. ALVW=(GVWR+VCW)/2

Appendix C: Comparison: Texas6 and FHWA Truck Classification Schemes

Texas6

Figure C-1: Texas 6 Class 1 — Motorcycles and Passenger Vehicles

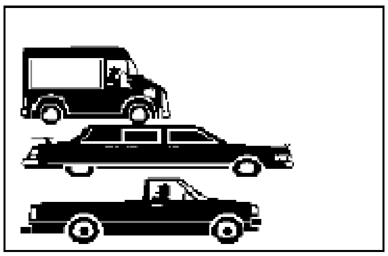


Figure C-2: Texas 6 Class 2 — 2 Axles, 4-Tire Single Units

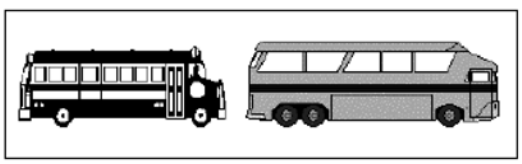


Figure C-3: Texas 6 Class 3 — Buses

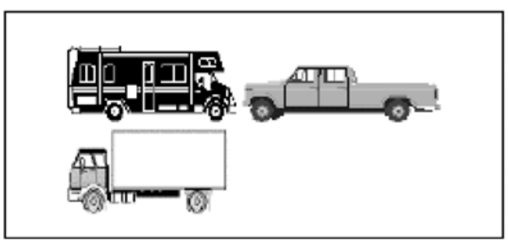


Figure C-4: Texas 6 Class 4 — 2D, 6-Tire Single Unit (Includes Handicapped-Equipped and Mini School Buses)

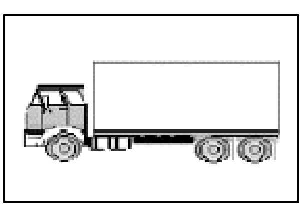


Figure C-5: Texas 6 Class 5 — 3 Axles, Single Unit

FHWA

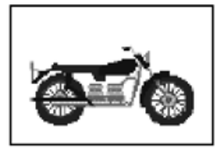


Figure C-14: FHWA Class 1 — Motorcycles

Figure C-15: FHWA Class 2 — Passenger Cars (With 1- or 2-Axle Trailers)

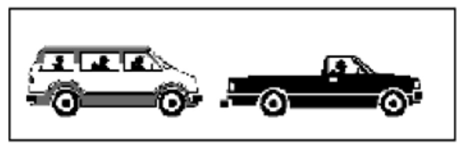


Figure C-16: FHWA Class 3 — 2 Axles, 4-Tire Single Units, Pickup, or Van (With 1- or
2-Axle Trailers)

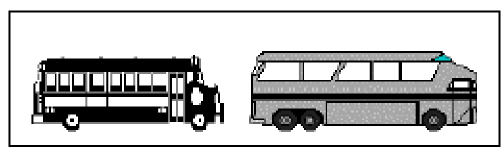


Figure C-17: FHWA Class 4 — Buses

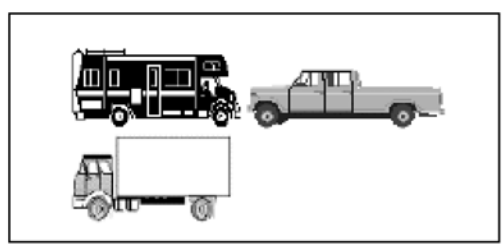


Figure C-18: FHWA Class 5 — 2D - 2 Axles, 6-Tire Single Units (Includes Handicapped-
Equipped Bus and Mini School Bus)

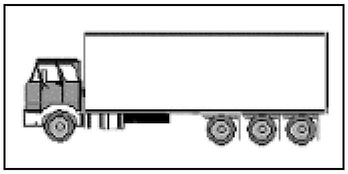


Figure C-6: Texas 6 Class 6 — 4 or More Axles, Single Unit

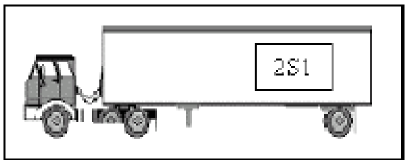


Figure C-7: Texas 6 Class 7 — 3 Axles, Single Trailer

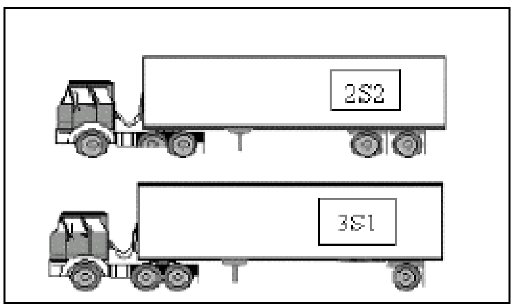


Figure C-8: Texas 6 Class 8 — 4 Axles, Single Trailer

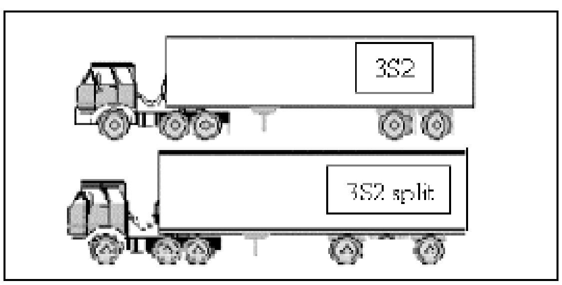


Figure C-9: Texas 6 Class 9 — 5 Axles, Single Trailer

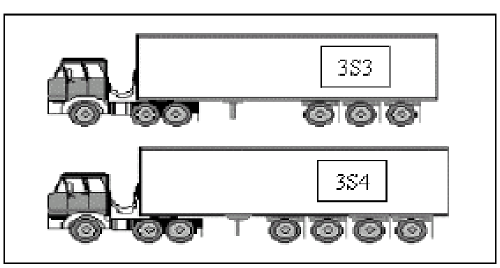


Figure C-10: Texas 6 Class 10 — 6 or More Axles, Single Trailer

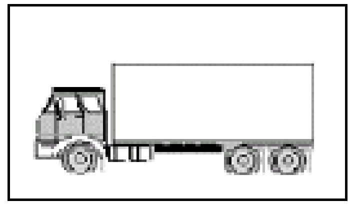


Figure C-19: FHWA Class 6 — 3 Axles, Single Unit

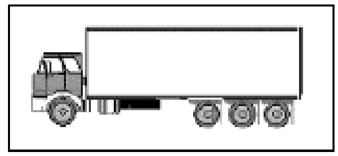


Figure C-20: FHWA Class 7 — 4 or More Axles, Single Unit

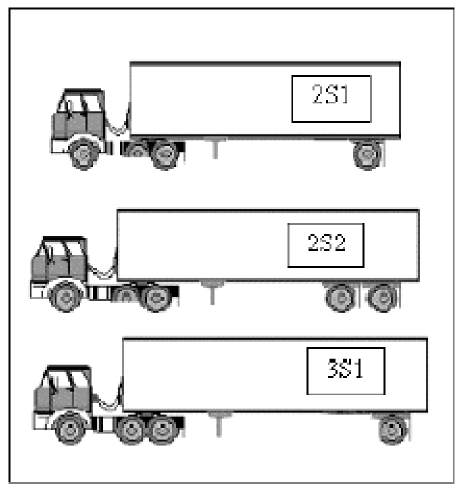


Figure C-21: FHWA Class 8 — 3 to 4 Axles, Single Trailer

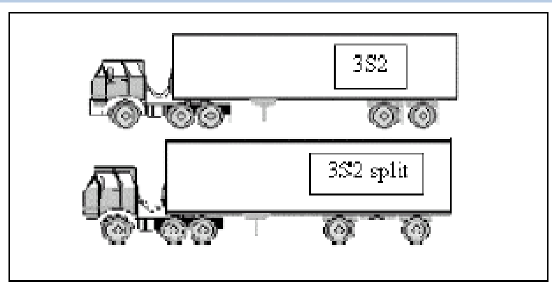


Figure C-22: FHWA Class 9 — 5 Axles, Single Trailer

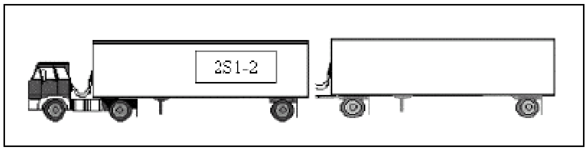


Figure C-11: Texas 6 Class 11 — 5 or Less Axles, Multi-Trailers

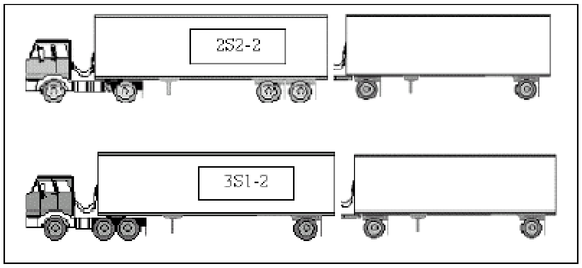


Figure C-12: Texas 6 Class 12 — 6 Axles, Multi-Trailers

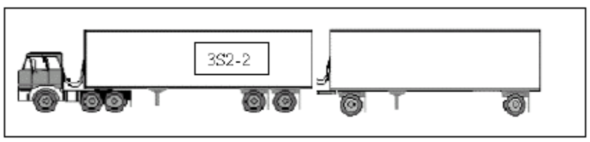


Figure C-13: Texas 6 Class 13 — 7 or More Axles, Multi-Trailers

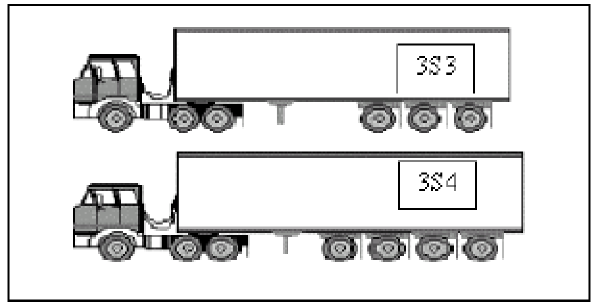


Figure C-23: FHWA Class 10 — 6 or More Axles, Single Trailer

Type equation here.

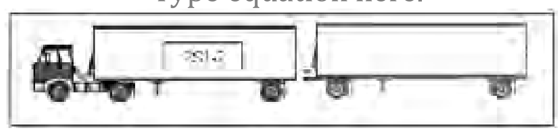


Figure C-24: FHWA Class 11 — 5 or Less Axles, Multi-Trailers

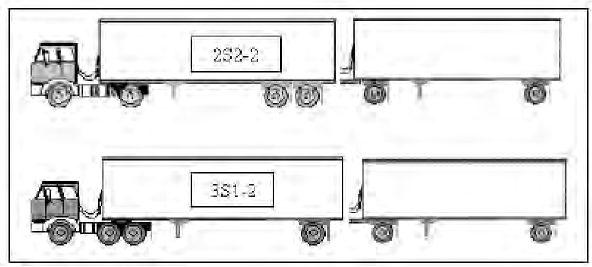


Figure C-25: FHWA Class 12 — 6 Axles, Multi-Trailers

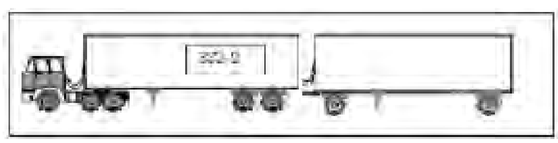


Figure C-26: FHWA Class 13 — 7 or More Axles, Multi-Trailers

Appendix D: About VTR Data

The Texas Vehicles, Titles, and Registrations Department provided data pulled from the database of current vehicle registrations as of August 2008. Below is analysis resulting from that data.

The number of actively registered cars, pickups trucks, SUVs, and vans of each model year were provided by VTR. The class of a vehicle (e.g. cars, pickups) was determined from the body type (VEHBDYTYPE) code in the VTR database, searched within the subset of “passenger cars” or “passenger trucks.” For example, cars consisted of sedans (VEHBDYTYPES 2D, 4D, 2H, 4H, SD, HB); station wagons (VEHBDYTZYPES SW, VT); sport cars (CP, CV, RD); and small crossovers classed as passenger cars (rather than passenger trucks) (VEHBDYTYPE LL).

Each class was further subdivided by weight ranges to delineate compact, midsize, and large subclasses (or just compact and large, in the case of pickups.) This succeeded in dividing the car class into compact, midsize, and large subclasses. This did not succeed for the pickup or SUV categories; the database returned a total number of weight-categorized vehicles that was substantially smaller than the overall number of vehicles in that class. For that reason, the data was thrown out.

Weight is not used to differential vehicle subclasses in the U.S. DOT classification scheme in regards to passenger cars. This is done by interior cargo capacity, which was not recorded in the VTR database. If the model of the vehicle were available that could be used to extract the subclass, but that information was not available. It was determined that using the VIN to lookup the model name posed a privacy concern. Because the traditional way of determining vehicle subclass was not available, vehicle weight was used. For this, the weight ranges of each subclass needed to be determined. This was statistically derived from the weights of vehicle models in each subclass.

VTR also provided a breakdown of vehicle registrations by make and vehicle model year for each of the three major classes examined.

Table D.1: Average age of vehicles by registration and by roadshare, registrations current as of Aug. 2008 and vehicle model years over 1988

Average Age	By Registrations	By Roadshare
Car	7.52	6.35
Compact	7.99	6.64
Midsize	7.37	6.33
Large	7.40	6.17
Truck	7.15	6.11
Pickup	7.73	6.55
SUV	5.79	5.14
Van	7.98	6.87
Total	**7.37**	**6.25**

Table D.2: Fleet Distribution from VTR Data

Veh Type	Roadshare (billon miles)	% of Group	% of Total	Registrations (Millions)	% of Group	% of Total
Car	103.5		57%	9.5		58%
Car*	*85.3*			*7.8*		
Compact	23.0	27%	15%	2.2	28%	16%
Midsize	32.4	38%	22%	2.9	38%	22%
Large	29.9	35%	20%	2.7	35%	20%
Truck	77.2		43%	7.0		42%
Pickup	48.5	63%	27%	4.5	65%	27%
SUV	24.9	32%	14%	2.1	30%	13%
Van	3.8	5%	2%	0.4	5%	2%

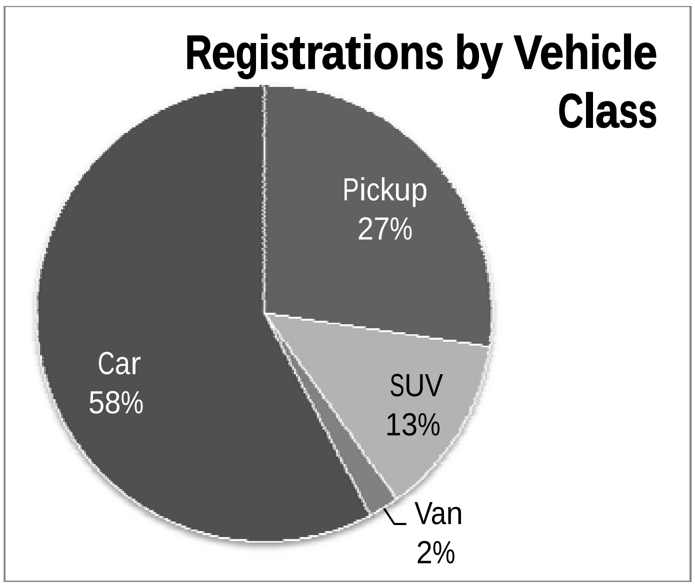


Figure D.1: Breakdown of VTR registrations by class, for cars actively registered as of August 2008

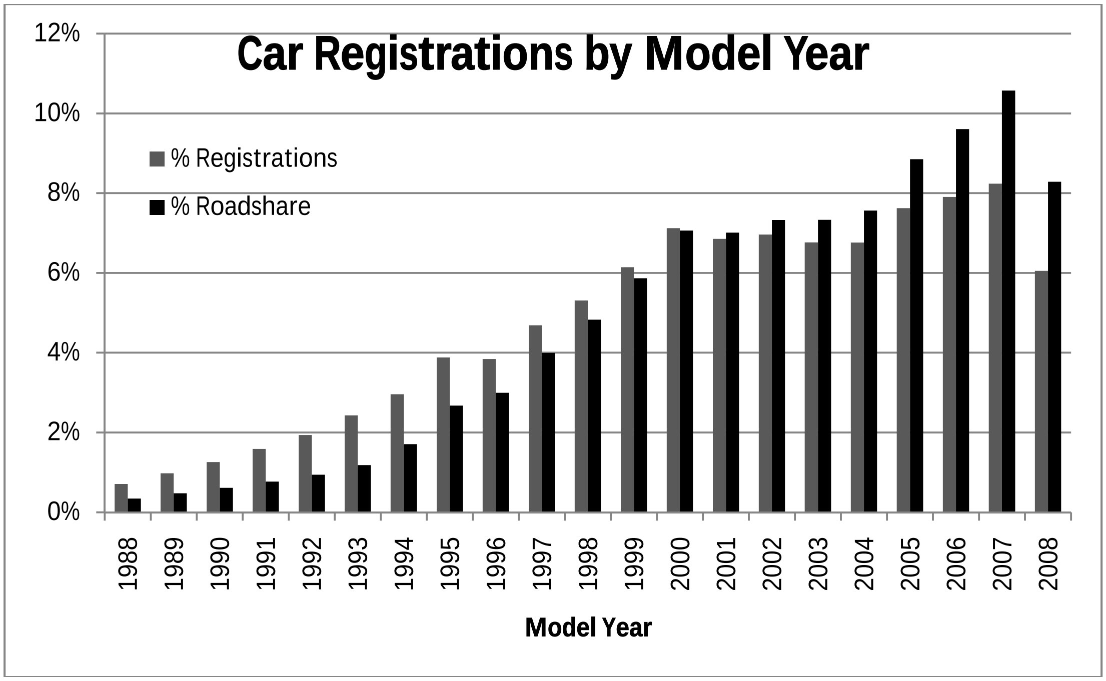


Figure D.2: Car registrations by model year, 1998–August 2008

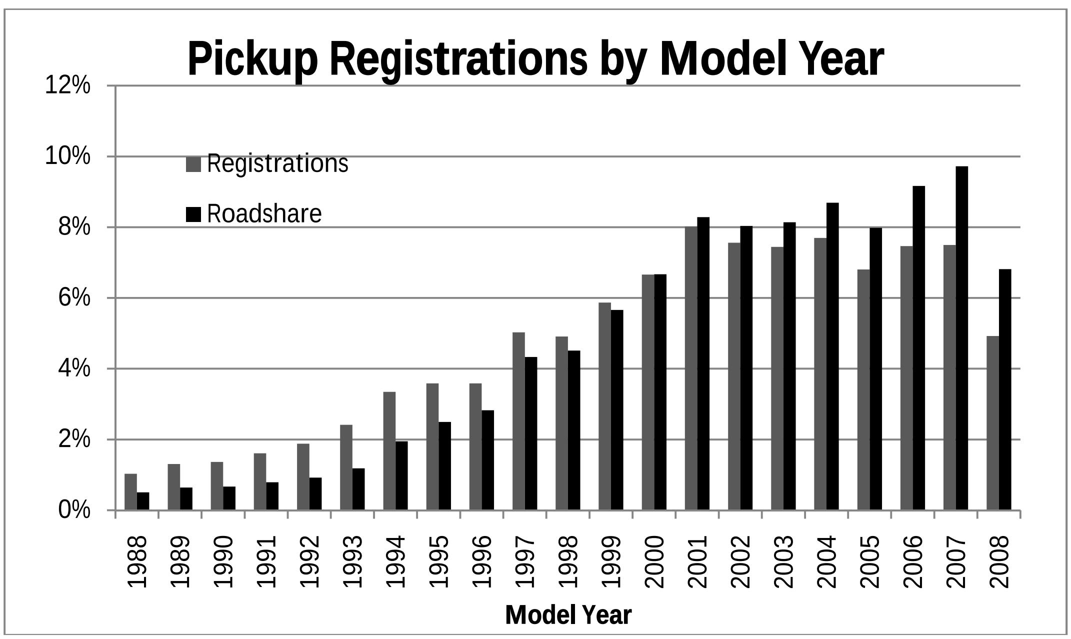


Figure D. 3: Pickup registrations by model year, as of August 2008

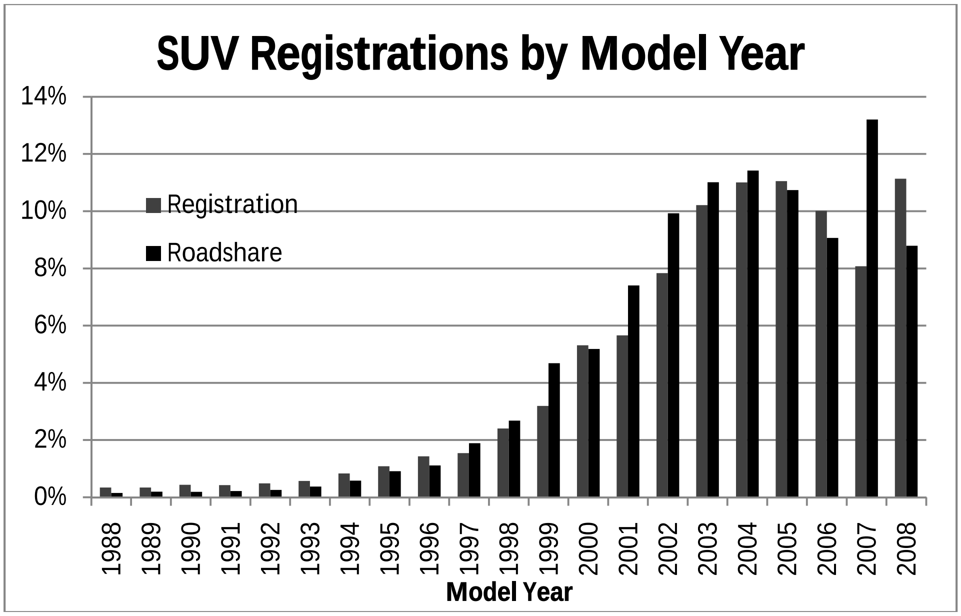


Figure D.3: SUV Registrations by model year, as of August 2008

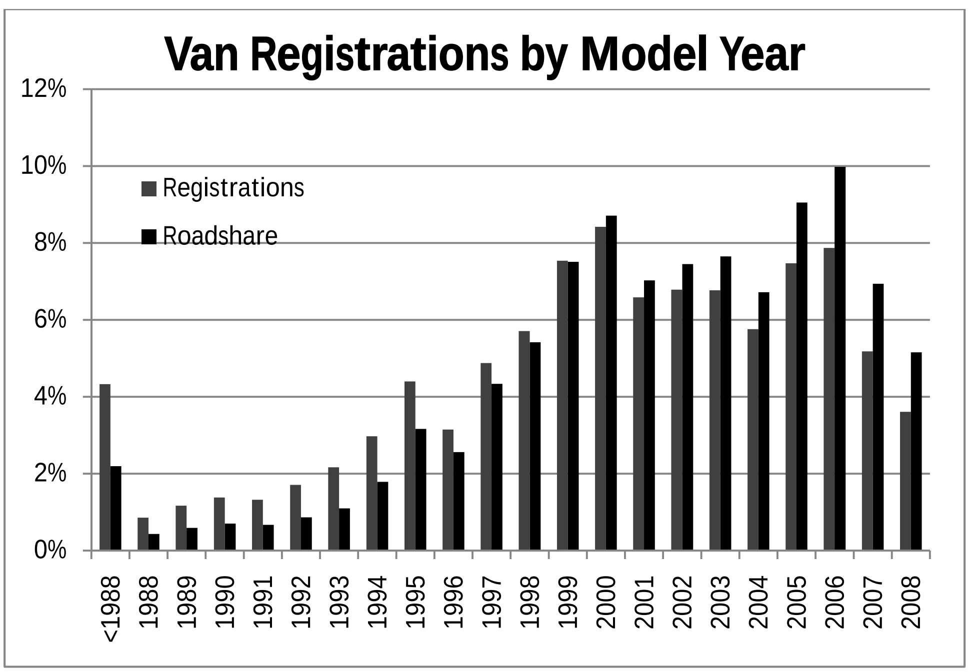


Figure D. 4: Van Registrations by model year, as of August 2008

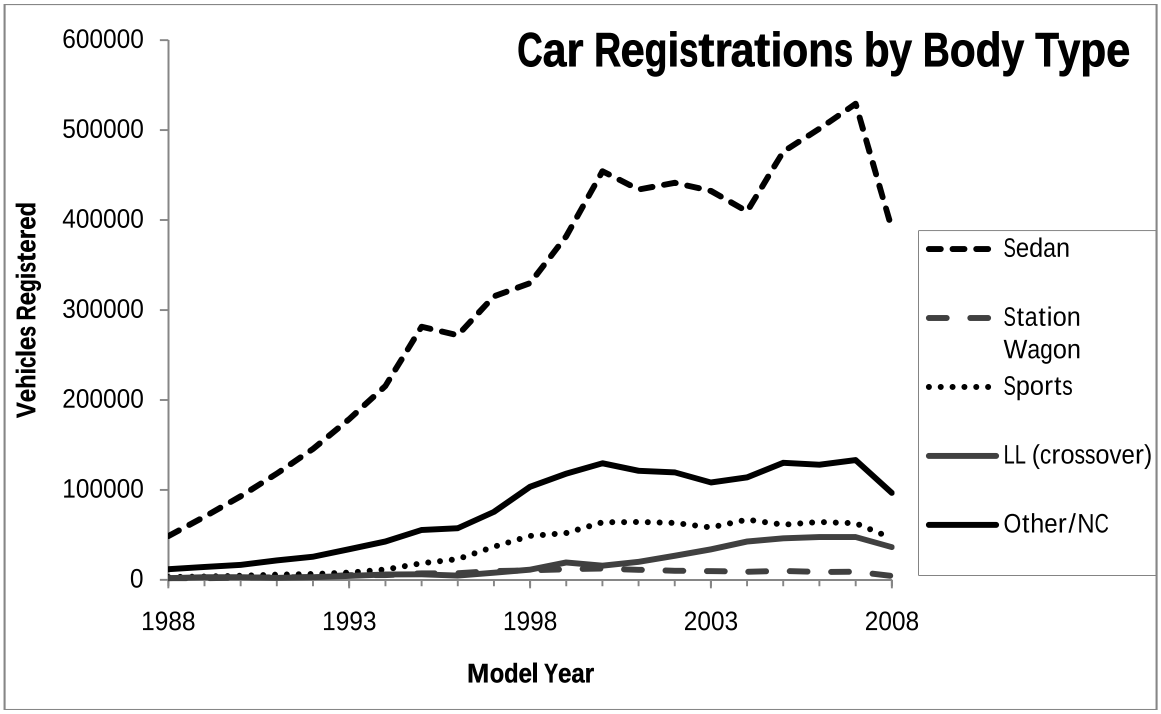


Figure D.5: Car registrations by body style, by model year, from 1998–August 2008

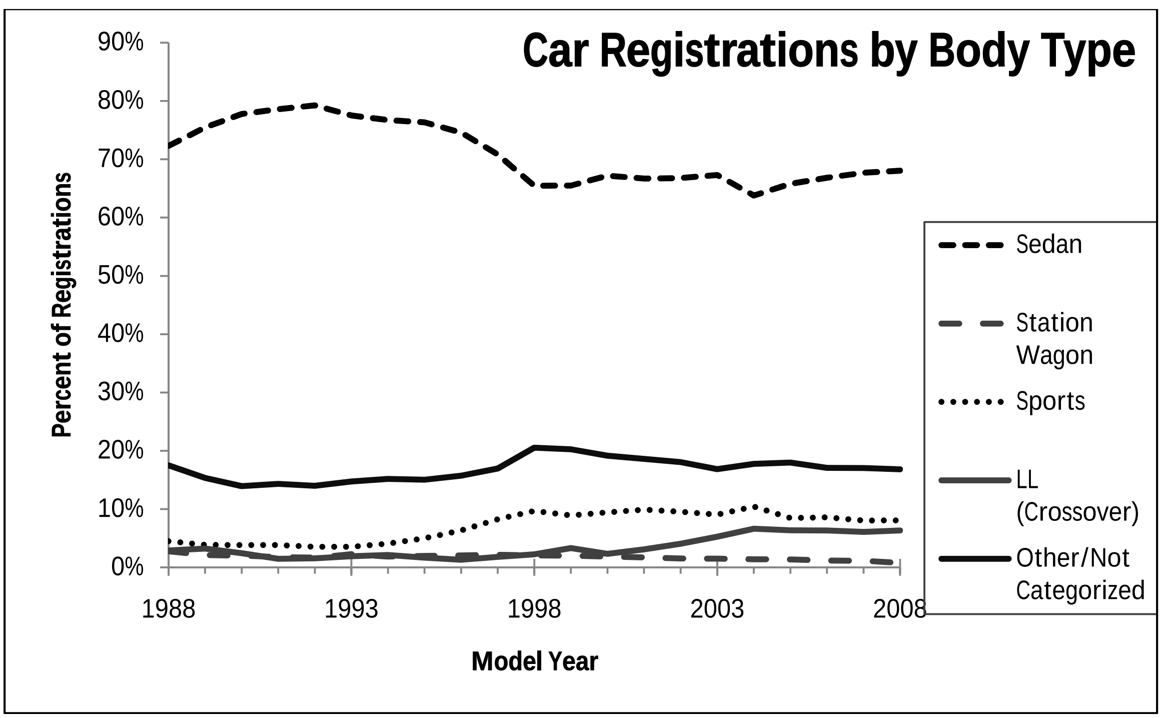


Figure D.6: Car body style registrations as a percentage of total car registration, by model year, from 1998–August 2008

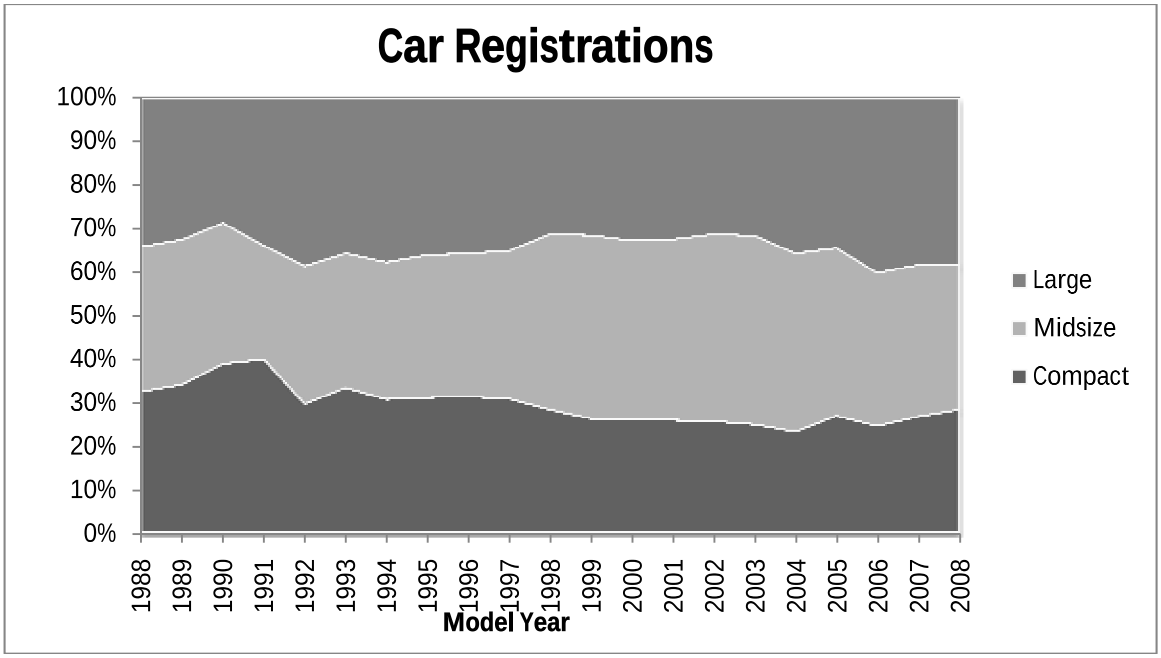


Figure D.7 Car registrations by subclass, per model year, from 1998–August 2008

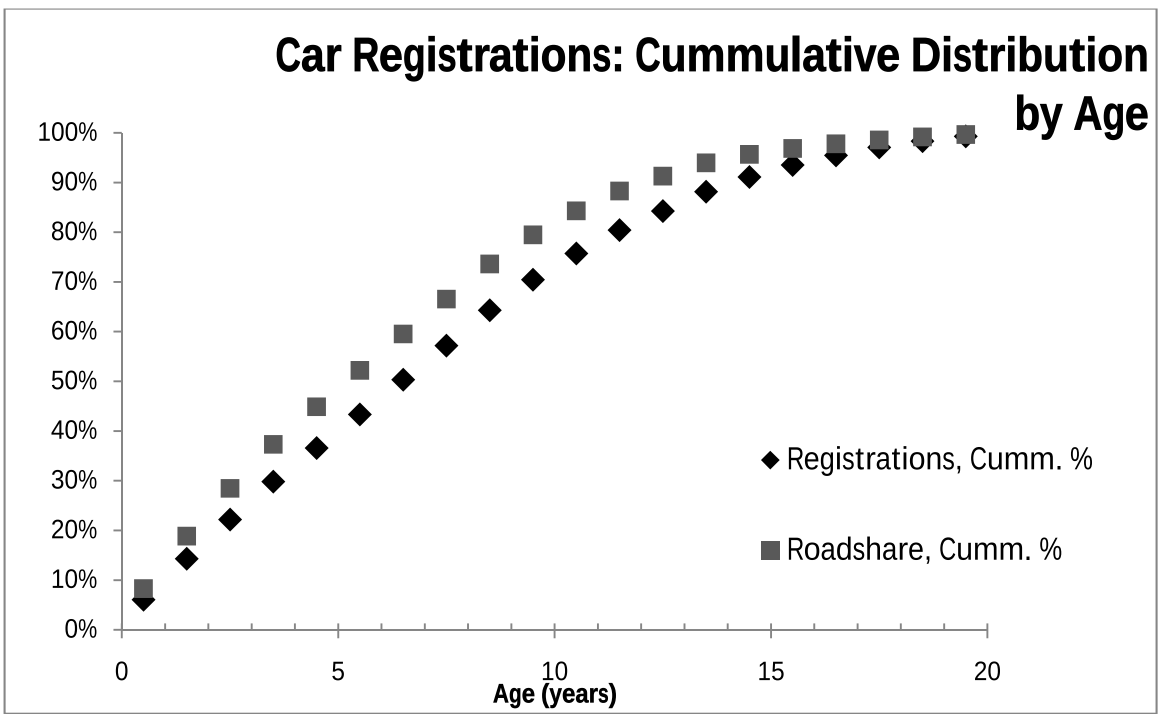


Figure D. 8: Cumulative distribution of car registrations/roadshare with age

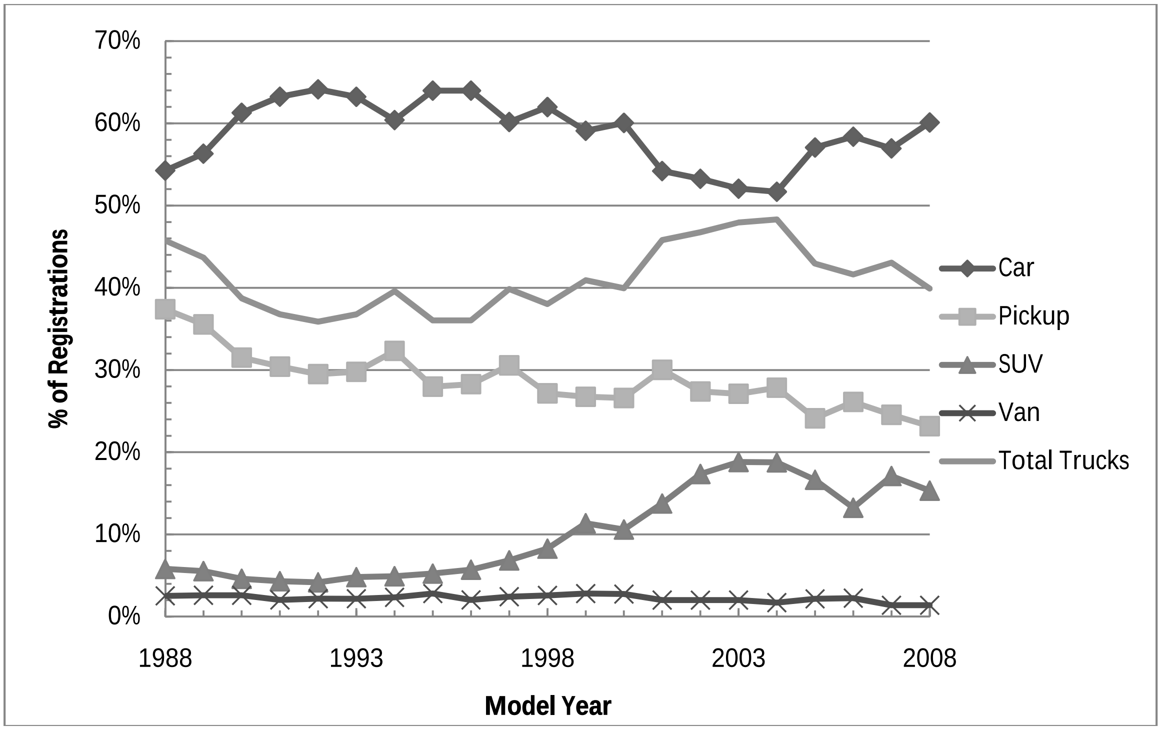


Figure D.9: Percent breakdown by class for registrations, by model year, from 1998–August 2008

Appendix E: Automotive News Sales Data

In order to build an informed picture of the current vehicle fleet, as well as ongoing trends, we looked at sales histories of vehicles. Specifically, we looked at Automotive News' databases of Automobile Sales by Nameplate for the U.S. for years 2002, 2003, 2004, 2005, and January–June 2007 and 2008. These results were given in terms of light cars and light trucks.

These vehicles were divided into our subcategories for compact, midsize, and large subcategories. We did not look at data for luxury vehicles or sports cars, as the objective was to find the most commonly driven vehicles.

This data was used to find the most commonly driven vehicles in a particular category, which were used to define the representative vehicles for that class.

An interesting phenomenon is the increasing popularity of "crossover" vehicles, which have shown a tendency to blend the line between cars and trucks. For example, a vehicle that fills much the same role as a station wagon and may only have a slightly larger footprint is classes as a compact SUV rather than a car. The crossovers also weight the SUV spectrum more towards the compact and midsize SUVs, which likely contributes to the trend wherein the proportion of compact SUVs to overall SUV sales rises from 2004-2008.

Overview

Table E.1: Vehicle Sales by Classes 2002-2008

All	2002	2003	2004	2005	2007	2008	Average
Cars	56.30%	53.29%	48.27%	49.57%	55.30%	60.07%	**54%**
SUVs	22.98%	24.95%	28.01%	26.87%	25.79%	23.84%	**25%**
Pickups	20.72%	21.76%	23.71%	23.56%	18.91%	16.09%	**21%**

Cars	2002	2003	2004	2005	2007	2008	Average
Cars	42.96%	43.53%	40.35%	39.29%	39.28%	42.40%	**41%**
SUVs	38.06%	36.96%	38.90%	39.39%	42.16%	43.33%	**40%**
Pickups	18.98%	19.51%	20.76%	21.32%	18.55%	14.27%	**19%**

SUVs	2002	2003	2004	2005	2007	2008	Average
Cars	30.98%	30.61%	29.85%	35.96%	43.62%	48.56%	**37%**
SUVs	42.34%	44.72%	47.93%	45.40%	40.49%	37.81%	**43%**
Pickups	26.68%	24.67%	22.22%	18.64%	15.89%	13.62%	**20%**

Pickups	2002	2003	2004	2005	2007	2008	Average
Compact	24.30%	23.82%	24.09%	23.94%	20.21%	21.70%	**23%**
Large	75.70%	76.18%	75.91%	76.06%	79.79%	78.30%	**77%**

Table E.2: Representative Vehicles

Representative Vehicles			
Compact Car	Toyota Corolla	Honda Civic	Ford Focus
Midsize Car	Toyota Camry	Honda Accord	Chevrolet Malibu
Large Car	For Taurus	Chevy Impala	Hyundai Sonata
Compact SUV	Jeep Liberty	Ford Escape	Honda CR-V
Midsize SUV	Ford Explorer	Jeep Grand Cherokee	Chevy Trailblazer
Large SUV	Chevy Tahoe	For Expedition	GMC Yukon
Compact Truck	Toyota Tacoma	Ford Ranger	Chevy Colorado
Large Truck	Ford F Series	Chevy Silverado	Dodge Ram

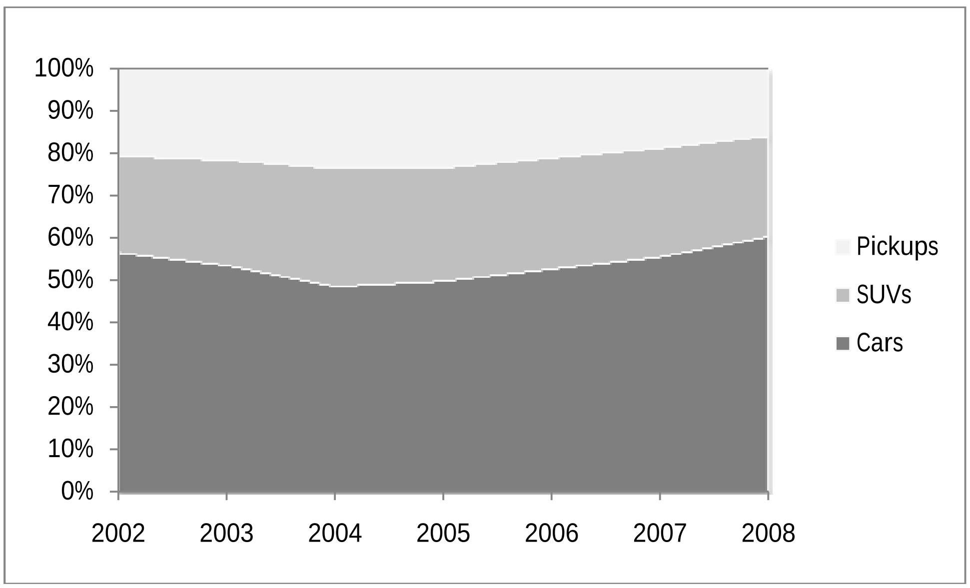


Figure E.1: Automotive Sales by Class

Cars

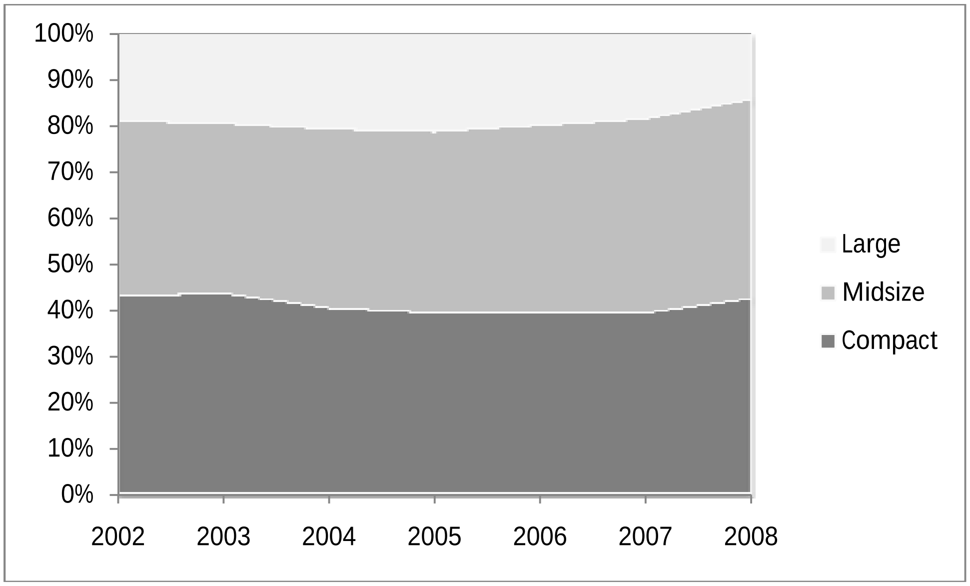


Figure E.2: Car Sales by Subclass

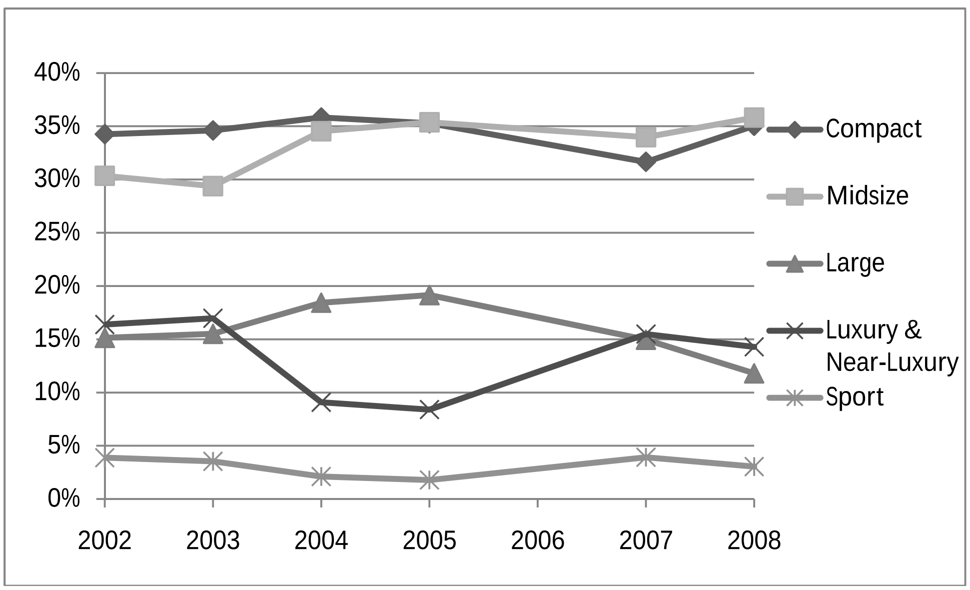


Figure E.3: Car Sales by Subclass, including Luxury and Near-Luxury category and Sports category

Compact Car

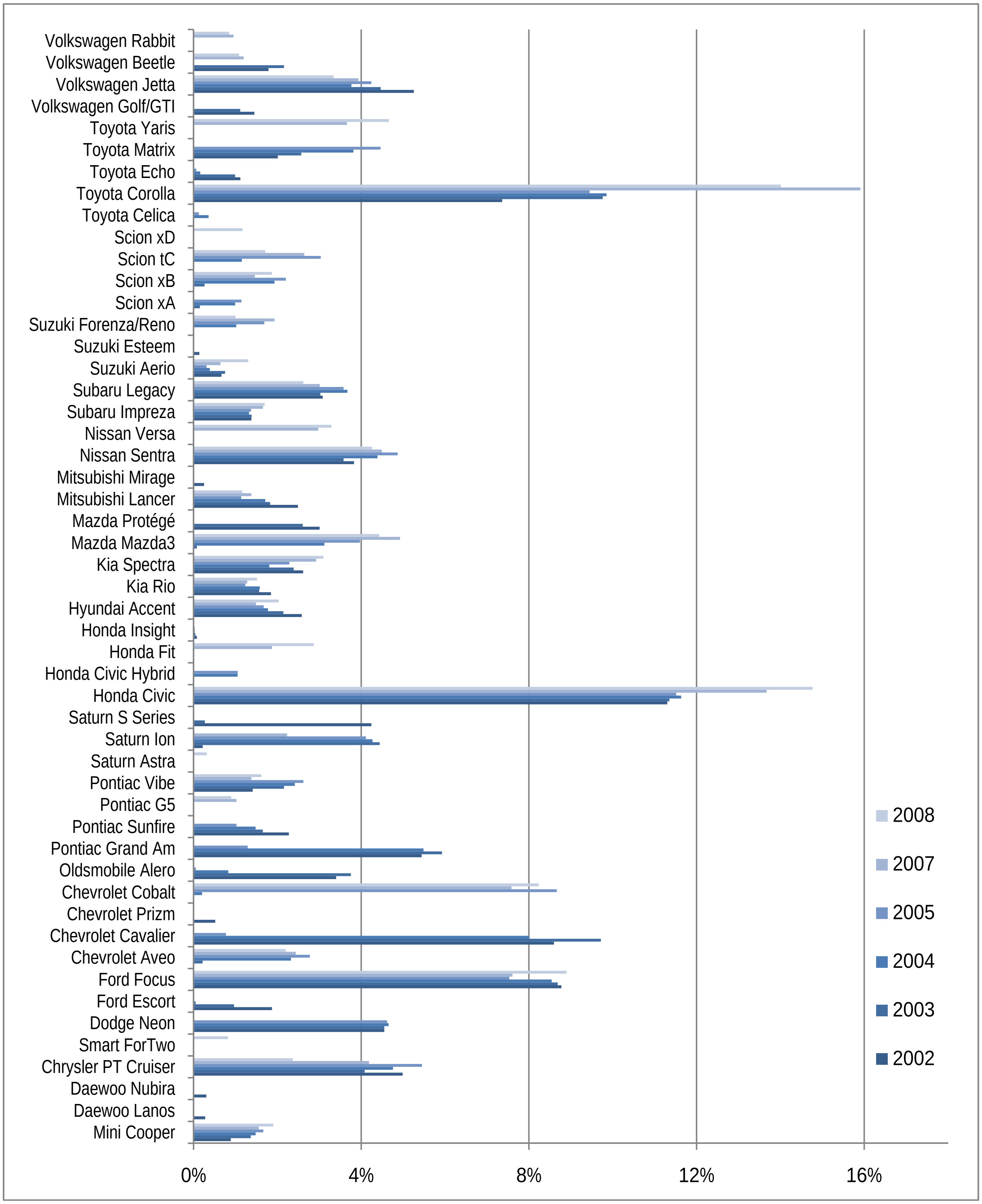


Figure E.4: Compact Car Sales by Model Nameplate

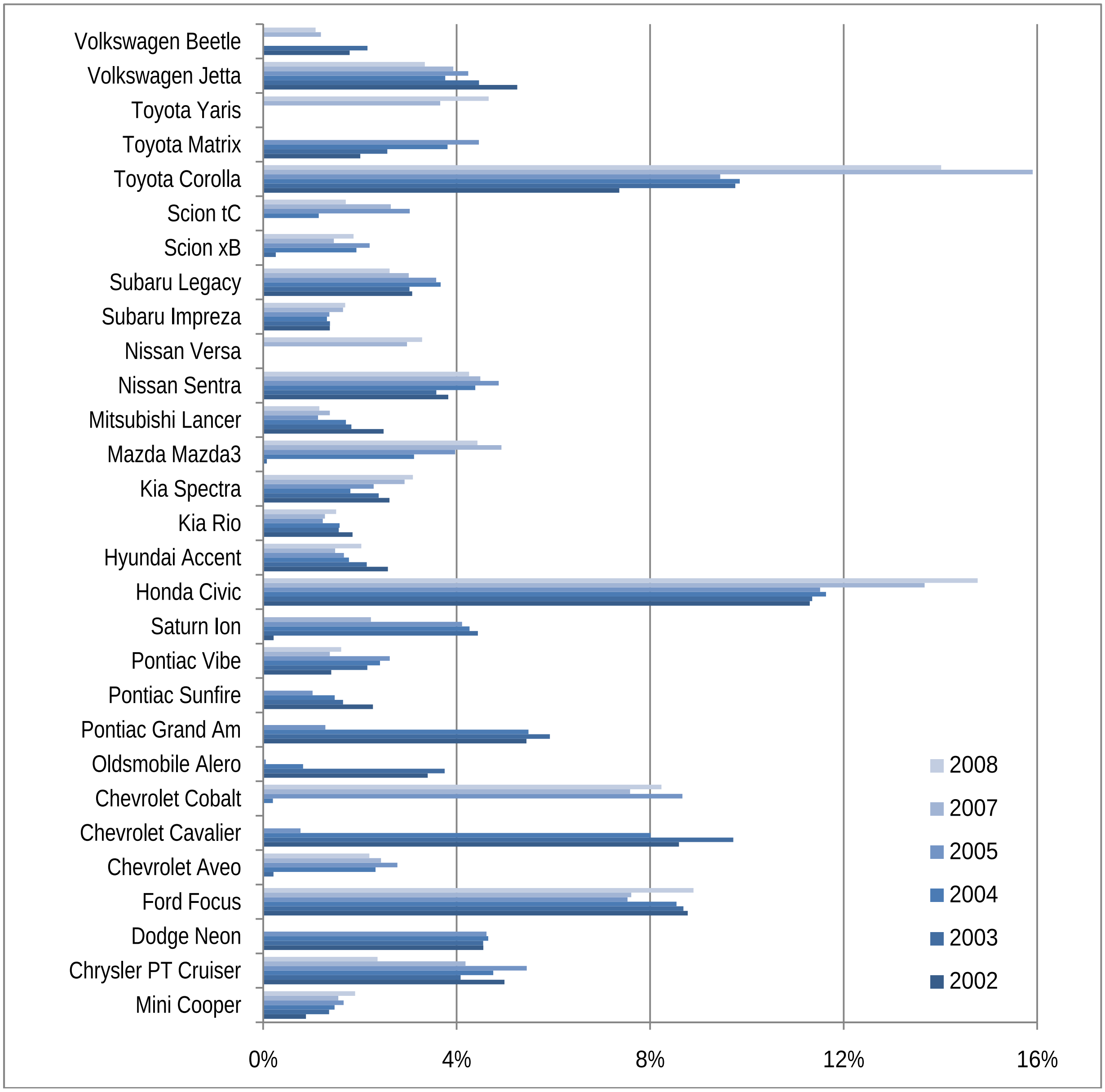


Figure E.5: Compact car sales by model nameplate, showing only models that comprised 1% or more of average percent yearly sales over 2002-2008.

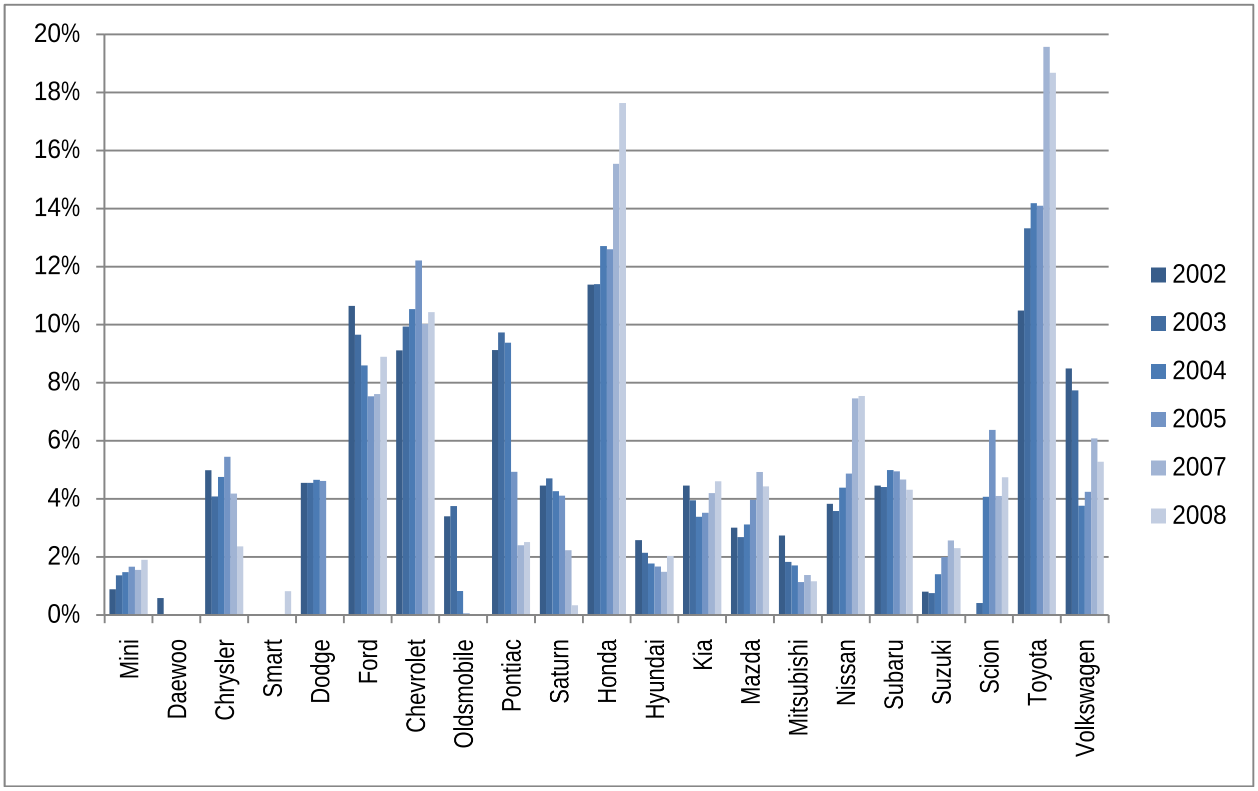


Figure E.6: Compact Car Sales by Make

Table E.3 Percent of Yearly Compact Sales by Make and Model

Compact Cars		Percent of yearly compact car sales						
Make	Model	2002%	2003%	2004%	2005%	2007%	2008%	Average
Mini	Mini Cooper	0.9	1.4	1.5	1.7	1.6	1.9	1.5%
Daewoo	Lanos	0.3	0.0	0.0	0.0	0.0	0.0	0.0%
Daewoo	Nubira	0.3	0.0	0.0	0.0	0.0	0.0	0.1%
Chrysler	PT Cruiser	5.0	4.1	4.8	5.5	4.2	2.4	4.3%
Smart	ForTwo	0.0	0.0	0.0	0.0	0.0	0.8	0.1%
Dodge	Neon	4.6	4.5	4.7	4.6	0.0	0.0	3.1%
Ford	Escort	1.9	1.0	0.0	0.0	0.0	0.0	0.5%
Ford	Focus	8.8	8.7	8.5	7.5	7.6	8.9	8.3%
Chevrolet	Aveo	0.0	0.2	2.3	2.8	2.4	2.2	1.7%
Chevrolet	Cavalier	8.6	9.7	8.0	0.8	0.0	0.0	4.5%
Chevrolet	Prizm	0.5	0.0	0.0	0.0	0.0	0.0	0.1%
Chevrolet	Cobalt	0.0	0.0	0.2	8.7	7.6	8.2	4.1%
Oldsmobile	Alero	3.4	3.8	0.8	0.1	0.0	0.0	1.3%
Pontiac	Grand Am	5.4	5.9	5.5	1.3	0.0	0.0	3.0%
Pontiac	Sunfire	2.3	1.7	1.5	1.0	0.0	0.0	1.1%
Pontiac	G5	0.0	0.0	0.0	0.0	1.0	0.9	0.3%
Pontiac	Vibe	1.4	2.2	2.4	2.6	1.4	1.6	1.9%
Saturn	Astra	0.0	0.0	0.0	0.0	0.0	0.3	0.1%
Saturn	Ion	0.2	4.4	4.3	4.1	2.2	0.0	2.5%
Saturn	S series	4.2	0.3	0.0	0.0	0.0	0.0	0.8%
Honda	Civic	11.3	11.4	11.6	11.5	13.7	14.8	12.4%
Honda	Civic Hybrid	0.0	0.0	1.0	1.1	0.0	0.0	0.4%
Honda	Fit	0.0	0.0	0.0	0.0	1.9	2.9	0.8%
Honda	Insight	0.1	0.0	0.0	0.0	0.0	0.0	0.0%
Hyundai	Accent	2.6	2.1	1.8	1.7	1.5	2.0	1.9%
Kia	Rio	1.8	1.6	1.6	1.2	1.3	1.5	1.5%
Kia	Spectra	2.6	2.4	1.8	2.3	2.9	3.1	2.5%
Mazda	Mazda3	0.0	0.1	3.1	4.0	4.9	4.4	2.8%
Mazda	Protégé	3.0	2.6	0.0	0.0	0.0	0.0	0.9%
Mitsubishi	Lancer I	2.5	1.8	1.7	1.1	1.4	1.2	1.6%
Mitsubishi	Mirage I	0.2	0.0	0.0	0.0	0.0	0.0	0.0%
Nissan	Sentra	3.8	3.6	4.4	4.9	4.5	4.3	4.2%
Nissan	Versa	0.0	0.0	0.0	0.0	3.0	3.3	1.0%
Subaru	Impreza	1.4	1.4	1.3	1.4	1.7	1.7	1.5%
Subaru	Legacy	3.1	3.0	3.7	3.6	3.0	2.6	3.2%
Suzuki	Aerio	0.7	0.8	0.4	0.3	0.6	1.3	0.7%

Compact Cars		Percent of yearly compact car sales						
Make	Model	2002%	2003%	2004%	2005%	2007%	2008%	Average
Suzuki	Esteem	0.1	0.0	0.0	0.0	0.0	0.0	0.0%
Suzuki	Forenza/Reno	0.0	0.0	1.0	1.7	1.9	1.0	0.9%
Scion	xA	0.0	0.2	1.0	1.1	0.0	0.0	0.4%
Scion	xB	0.0	0.3	1.9	2.2	1.5	1.9	1.3%
Scion	tC	0.0	0.0	1.2	3.0	2.6	1.7	1.4%
Scion	xD	0.0	0.0	0.0	0.0	0.0	1.2	0.2%
Toyota	Celica	0.0	0.0	0.4	0.1	0.0	0.0	0.1%
Toyota	Corolla	7.4	9.8	9.9	9.4	15.9	14.0	11.1%
Toyota	Echo	1.1	1.0	0.2	0.1	0.0	0.0	0.4%
Toyota	Matrix	2.0	2.6	3.8	4.5	0.0	0.0	2.1%
Toyota	Yaris	0.0	0.0	0.0	0.0	3.7	4.7	1.4%
Volkswagen	Cabrio (Golf)	0.3	0.0	0.0	0.0	0.0	0.0	0.1%
Volkswagen	Golf/GTI	1.1	1.1	0.0	0.0	0.0	0.0	0.4%
Volkswagen	Jetta	5.3	4.5	3.8	4.2	3.9	3.3	4.2%
Volkswagen	New Beetle	1.8	2.2	0.0	0.0	1.2	1.1	1.0%
Volkswagen	Rabbit	0.0	0.0	0.0	0.0	1.0	0.9	0.3%

Midsize Car

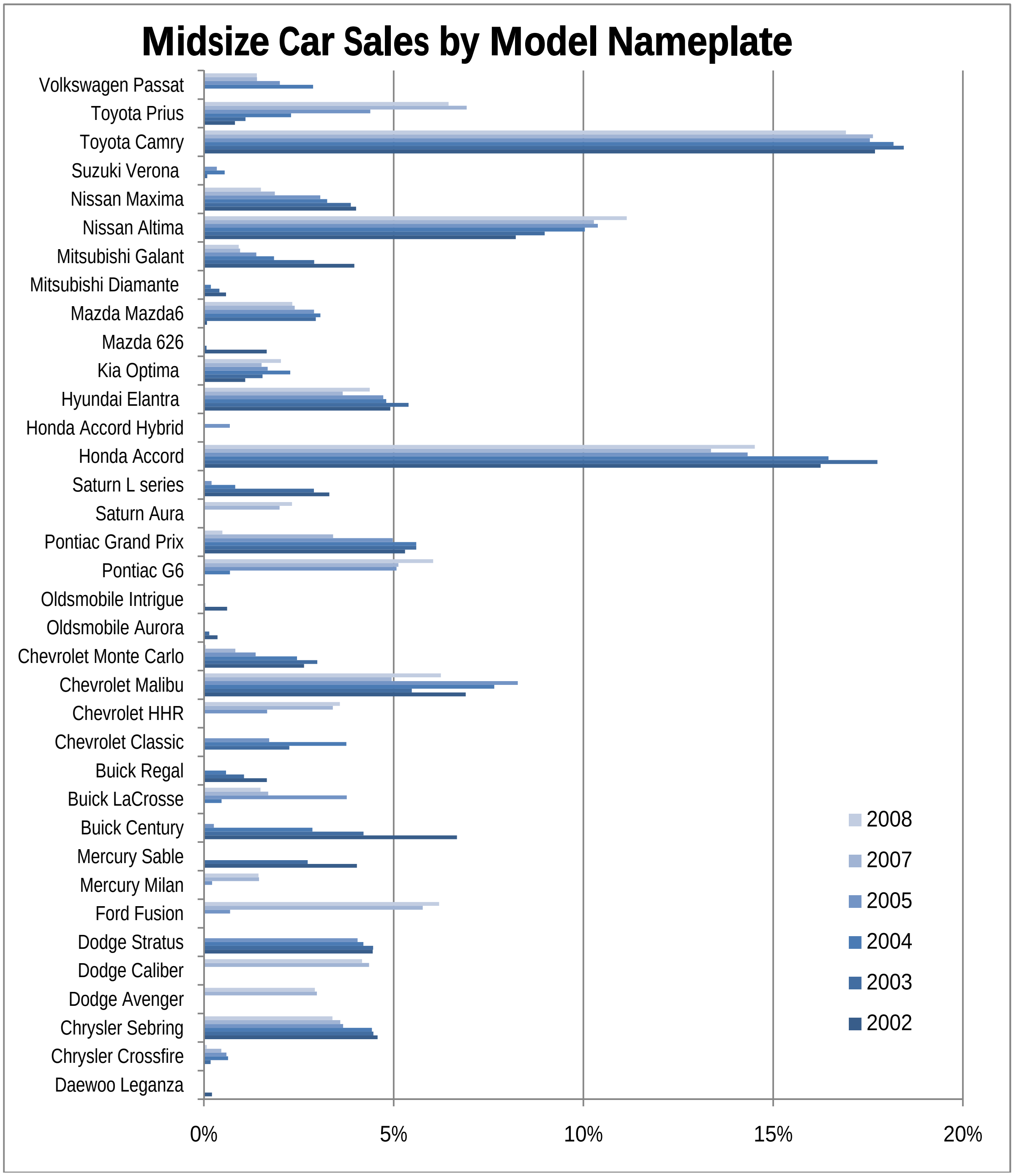


Figure E.7: Midsize Car Sales by Model Nameplate

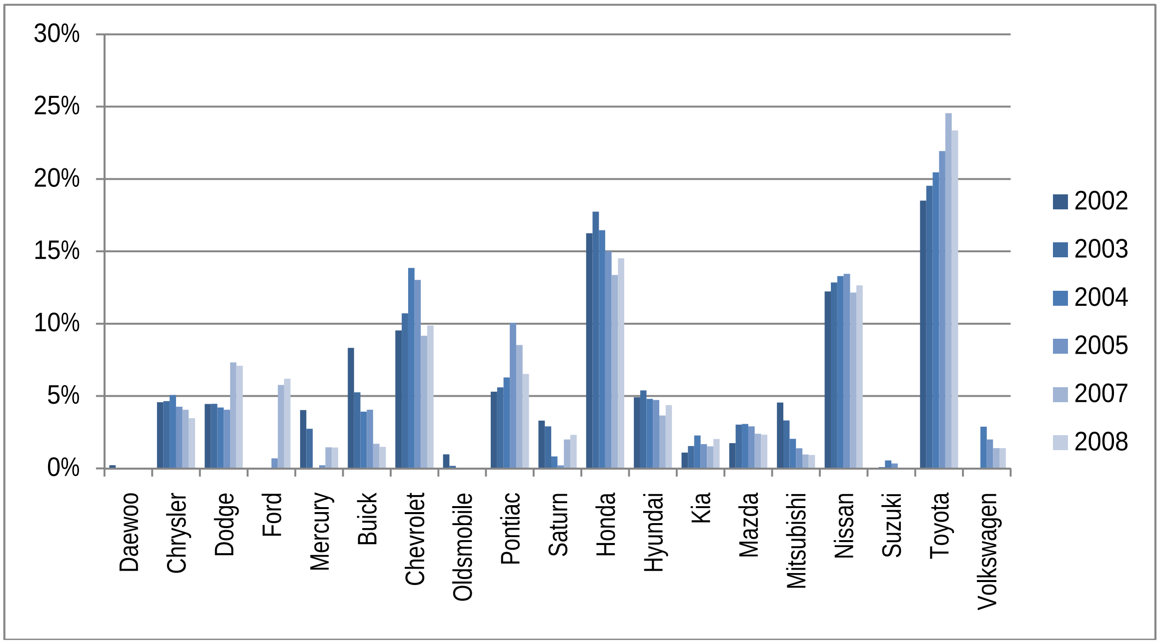


Figure E.8: Midsize Car Sales by Make

Table E.4 Percent of Yearly Midsize Sales by Make and Model

Midsize Cars		Percent of yearly midsize car sales						
Make	Model	2002	2003	2004	2005	2007	2008	Average
Daewoo	Leganza	0.2	0.0	0.0	0.0	0.0	0.0	0.0%
Chrysler	Crossfire	0.0	0.2	0.6	0.6	0.5	0.1	0.3%
Chrysler	Sebring	4.6	4.5	4.4	3.7	3.6	3.4	4.0%
Dodge	Avenger	0.0	0.0	0.0	0.0	3.0	2.9	1.0%
Dodge	Caliber	0.0	0.0	0.0	0.0	4.4	4.2	1.4%
Dodge	Stratus	4.4	4.5	4.2	4.1	0.0	0.0	2.9%
Ford	Fusion	0.0	0.0	0.0	0.7	5.8	6.2	2.1%
Mercury	Milan	0.0	0.0	0.0	0.2	1.5	1.4	0.5%
Mercury	Sable	4.0	2.7	0.0	0.0	0.0	0.0	1.1%
Buick	Century	6.7	4.2	2.9	0.3	0.0	0.0	2.3%
Buick	LaCrosse	0.0	0.0	0.5	3.8	1.7	1.5	1.2%
Buick	Regal	1.7	1.1	0.6	0.0	0.0	0.0	0.6%
Chevrolet	Classic	0.0	2.3	3.8	1.7	0.0	0.0	1.3%
Chevy	HHR	0.0	0.0	0.0	1.7	3.4	3.6	1.4%
Chevrolet	Malibu	6.9	5.5	7.7	8.3	4.9	6.2	6.6%
Chevrolet	Monte Carlo	2.6	3.0	2.5	1.4	0.8	0.0	1.7%
Oldsmobile	Aurora	0.4	0.1	0.0	0.0	0.0	0.0	0.1%
Oldsmobile	Intrigue	0.6	0.0	0.0	0.0	0.0	0.0	0.1%
Pontiac	G6	0.0	0.0	0.7	5.1	5.1	6.0	2.8%
Pontiac	Grand Prix	5.3	5.6	5.6	5.0	3.4	0.5	4.2%
Saturn	Aura	0.0	0.0	0.0	0.0	2.0	2.3	0.7%
Saturn	L series	3.3	2.9	0.8	0.2	0.0	0.0	1.2%
Honda	Accord	16.3	17.7	16.5	14.3	13.4	14.5	15.4%
Honda	Accord Hybrid	0.0	0.0	0.0	0.7	0.0	0.0	0.1%
Hyundai	Elantra	4.9	5.4	4.8	4.7	3.7	4.4	4.6%
Kia	Optima	1.1	1.5	2.3	1.7	1.5	2.0	1.7%
Mazda	626	1.7	0.1	0.0	0.0	0.0	0.0	0.3%
Mazda	Mazda6	0.1	3.0	3.1	2.9	2.4	2.3	2.3%
Mitsubishi	Diamante	0.6	0.4	0.2	0.0	0.0	0.0	0.2%
Mitsubishi	Galant	4.0	2.9	1.9	1.4	1.0	0.9	2.0%
Nissan	Altima	8.2	9.0	10.0	10.4	10.3	11.1	9.8%
Nissan	Maxima	4.0	3.9	3.2	3.1	1.9	1.5	2.9%
Suzuki	Verona	0.0	0.1	0.5	0.3	0.0	0.0	0.2%
Toyota	Camry	17.7	18.4	18.2	17.5	17.6	16.9	17.7%

Midsize Cars		Percent of yearly midsize car sales						
Make	Model	2002	2003	2004	2005	2007	2008	Average
Toyota	Prius	0.8	1.1	2.3	4.4	6.9	6.4	3.7%
Volkswagen	Passat	0.0	0.0	2.9	2.0	1.4	1.4	1.3%

Large Cars

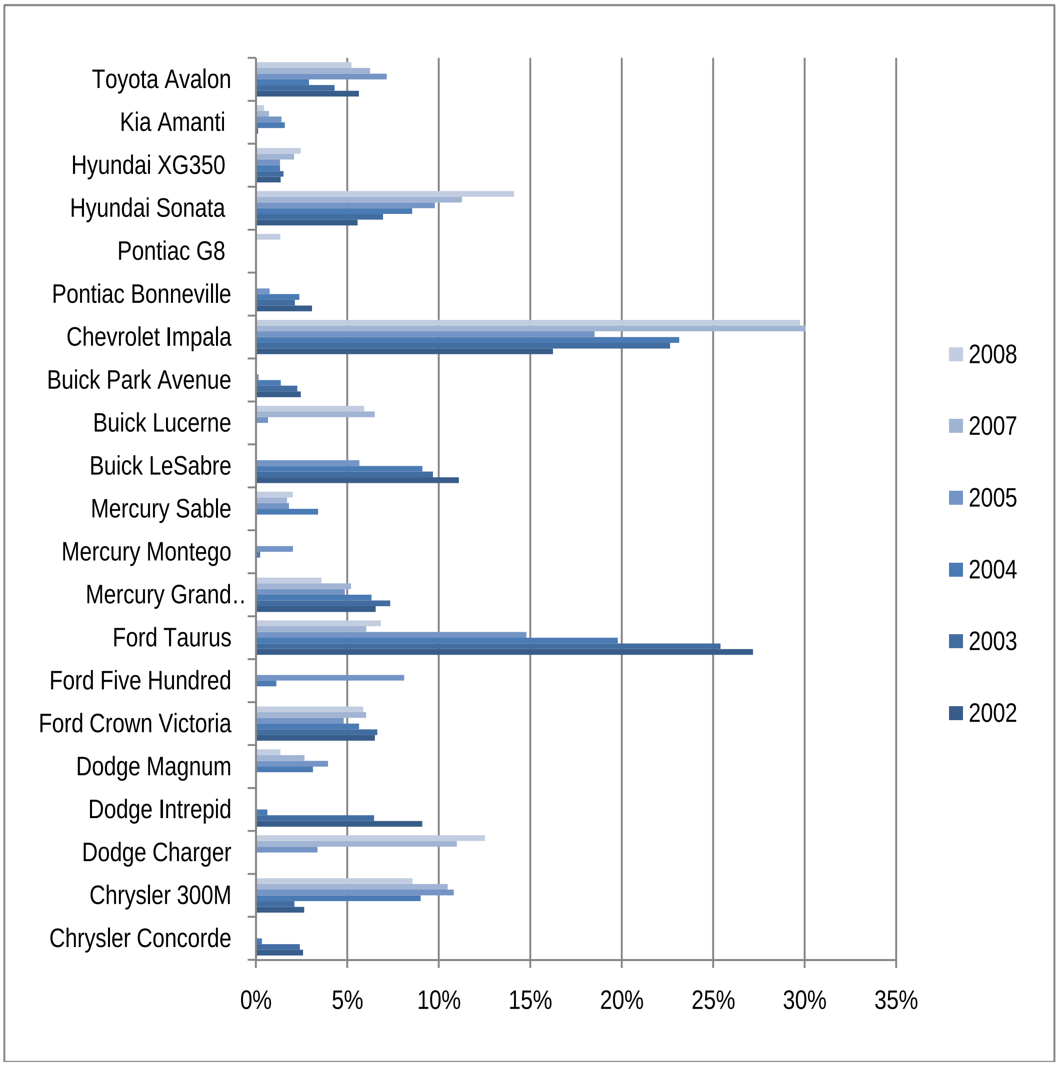


Figure E.9: Large Car Sales by Model Nameplate

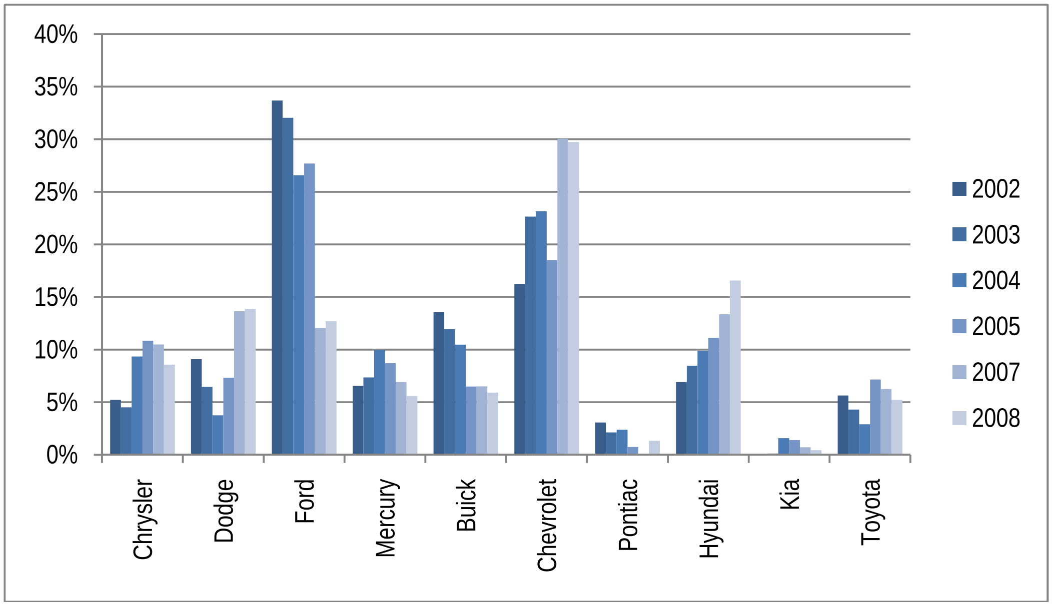


Figure E.10: Large Car Sales by Make

Table E.5: Percent of Yearly Large Car Sales by Make and Model

Large Car		Percent of yearly large car sales						
Make	Model	2002	2003	2004	2005	2007	2008	Average
Chrysler	Concorde	2.6	2.4	0.3	0.0	0.0	0.0	0.9%
Chrysler	300M	2.6	2.1	9.0	10.8	10.5	8.6	7.3%
Dodge	Charger	0.0	0.0	0.0	3.4	11.0	12.5	4.5%
Dodge	Intrepid	9.1	6.5	0.6	0.0	0.0	0.0	2.7%
Dodge	Magnum	0.0	0.0	3.1	3.9	2.7	1.3	1.8%
Ford	Crown Victoria	6.5	6.6	5.6	4.8	6.0	5.9	5.9%
Ford	Five Hundred	0.0	0.0	1.1	8.1	0.0	0.0	1.5%
Ford	Taurus	27.2	25.4	19.8	14.8	6.0	6.8	16.7%
Mercury	Grand Marquis	6.6	7.4	6.3	4.9	5.2	3.6	5.6%
Mercury	Montego	0.0	0.0	0.2	2.0	0.0	0.0	0.4%
Mercury	Sable	0.0	0.0	3.4	1.8	1.7	2.0	1.5%
Buick	LeSabre	11.1	9.7	9.1	5.7	0.0	0.0	5.9%
Buick	Lucerne	0.0	0.0	0.0	0.7	6.5	5.9	2.2%
Buick	Park Avenue	2.5	2.3	1.4	0.2	0.0	0.0	1.0%
Chevrolet	Impala	16.2	22.6	23.1	18.5	30.0	29.7	23.4%
Pontiac	Bonneville	3.1	2.1	2.4	0.8	0.0	0.0	1.4%
Pontiac	G8	0.0	0.0	0.0	0.0	0.0	1.3	0.2%
Hyundai	Sonata	5.6	7.0	8.5	9.8	11.3	14.1	9.4%
Hyundai	XG350	1.4	1.5	1.3	1.3	2.1	2.4	1.7%
Kia	Amanti	0.0	0.1	1.6	1.4	0.7	0.4	0.7%
Toyota	Avalon	5.6	4.3	2.9	7.2	6.2	5.2	5.2%

Pickups

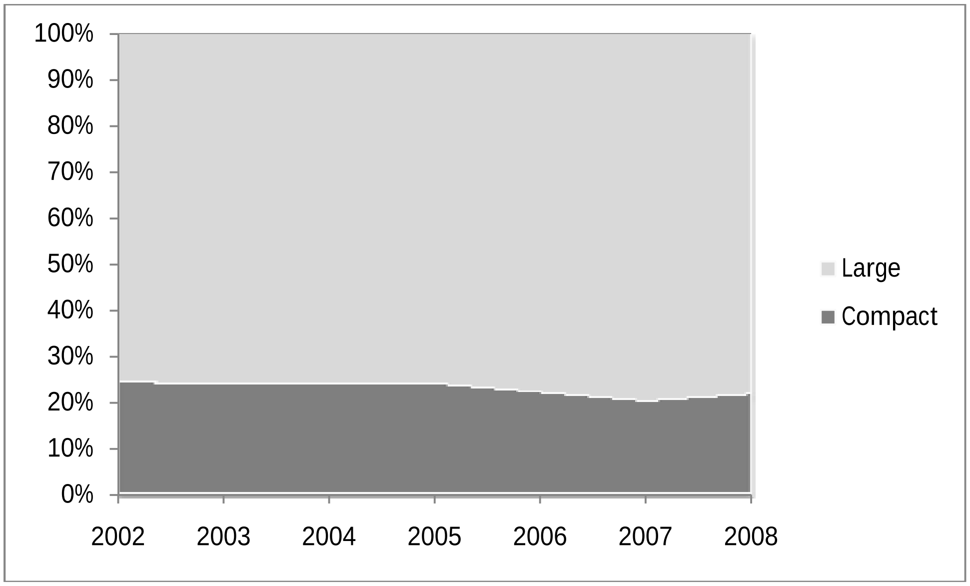


Figure E.11: Pickup Sales by Subclass

Compact

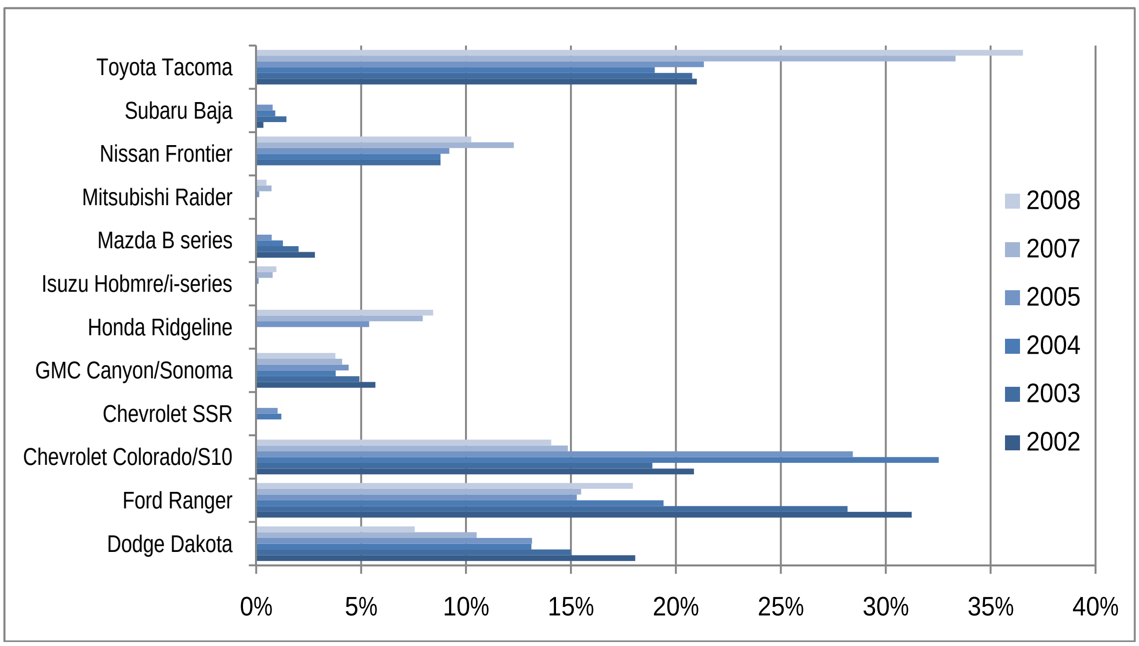


Figure E.12: Compact Truck Sales by Model Nameplate

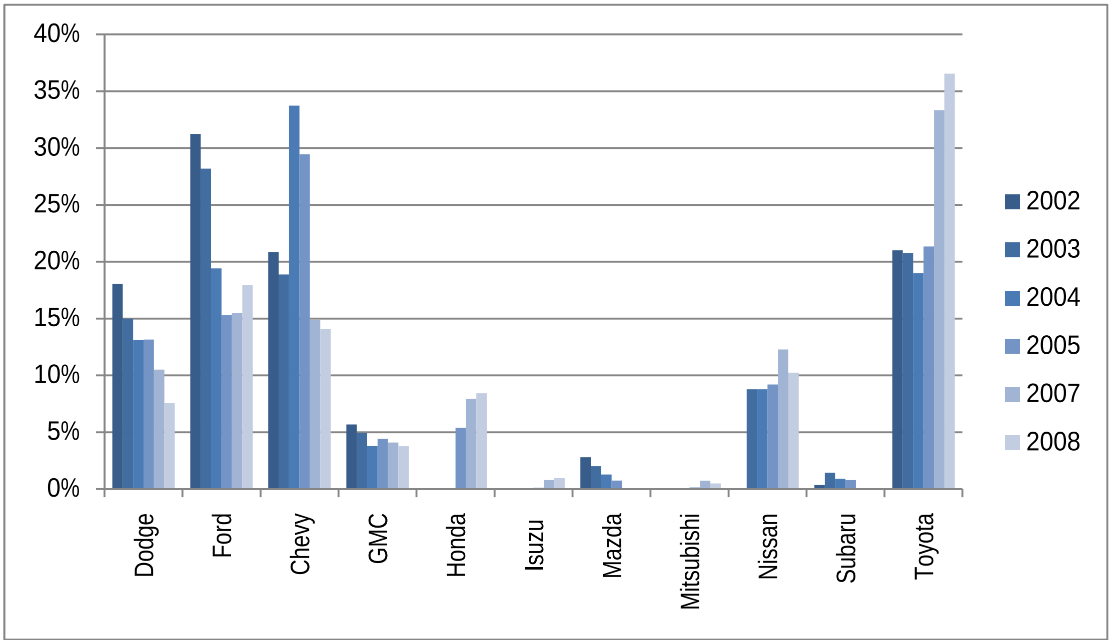


Figure E.13: Compact Pickup Sales by Make

Table E.6: Percent of Yearly Compact Truck Sales by Make and Model

Compact Truck		Percent of yearly compact truck sales						
Make	Model	2002	2003	2004	2005	2007	2008	Average
Dodge	Dakota	18.1	15.0	13.1	13.1	10.5	7.6	12.9%
Ford	Ranger	31.2	28.2	19.4	15.3	15.5	18.0	21.3%
Chevy	Colorado/S10	20.9	18.9	32.5	28.4	14.9	14.1	21.6%
Chevy	SSR	0.0	0.0	1.2	1.0	0.0	0.0	0.4%
GMC	Canyon/Sonoma	5.7	4.9	3.8	4.4	4.1	3.8	4.4%
Honda	Ridgeline	0.0	0.0	0.0	5.4	7.9	8.4	3.6%
Isuzu	Hobmre/i-series	0.0	0.0	0.0	0.1	0.8	1.0	0.3%
Mazda	B series	2.8	2.0	1.3	0.7	0.0	0.0	1.1%
Mitsubishi	Raider	0.0	0.0	0.0	0.1	0.7	0.5	0.2%
Nissan	Frontier	0.0	8.8	8.8	9.2	12.3	10.2	8.2%
Subaru	Baja	0.3	1.4	0.9	0.8	0.0	0.0	0.6%
Toyota	Tacoma	21.0	20.8	19.0	21.3	33.3	36.5	25.3%

Large

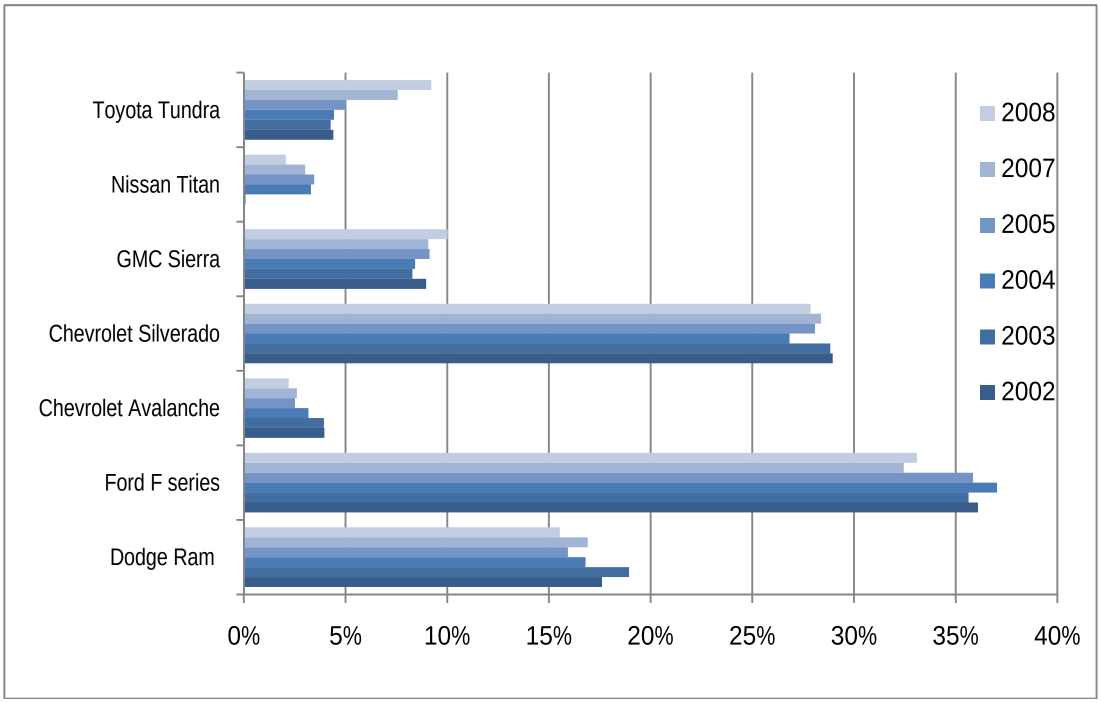


Figure E.14: Large Pickup Sales by Model Nameplate

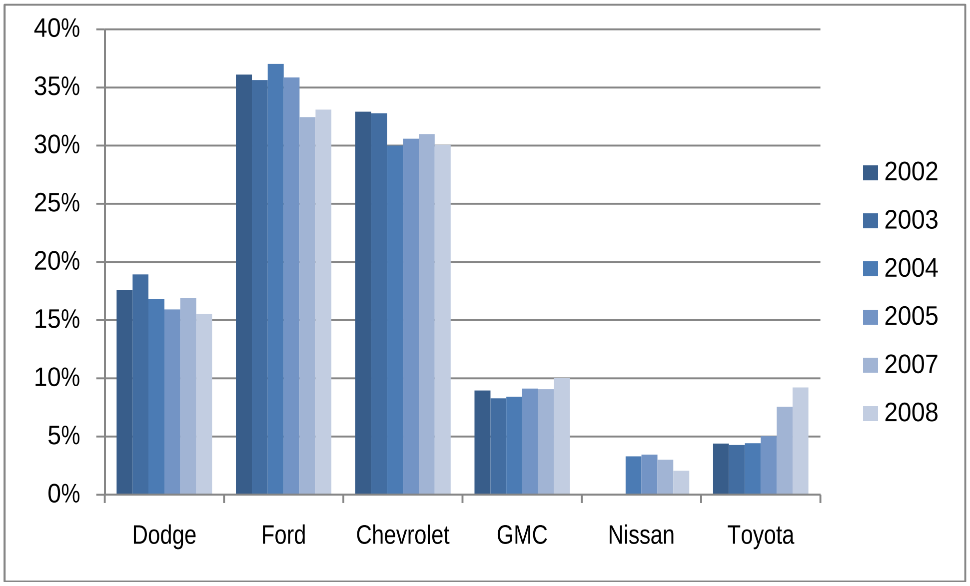


Figure E.15: Large Pickup Sales by Make

Table E.7: Percent of Yearly Large Truck Sales by Make and Model

Large Truck		Percent of yearly large truck sales						
Make	Model	2002	2003	2004	2005	2007	2008	Average
Dodge	Ram	17.6	18.9	16.8	15.9	16.9	15.5	17.0%
Ford	F series	36.1	35.6	37.0	35.9	32.4	33.1	35.0%
Chevrolet	Avalanche	4.0	3.9	3.2	2.5	2.6	2.2	3.1%
Chevrolet	Silverado	29.0	28.8	26.8	28.1	28.4	27.9	28.2%
GMC	Sierra	9.0	8.3	8.4	9.1	9.1	10.0	9.0%
Nissan	Titan	0.0	0.1	3.3	3.5	3.0	2.1	2.0%
Toyota	Tundra	4.4	4.3	4.4	5.0	7.6	9.2	5.8%

SUVs

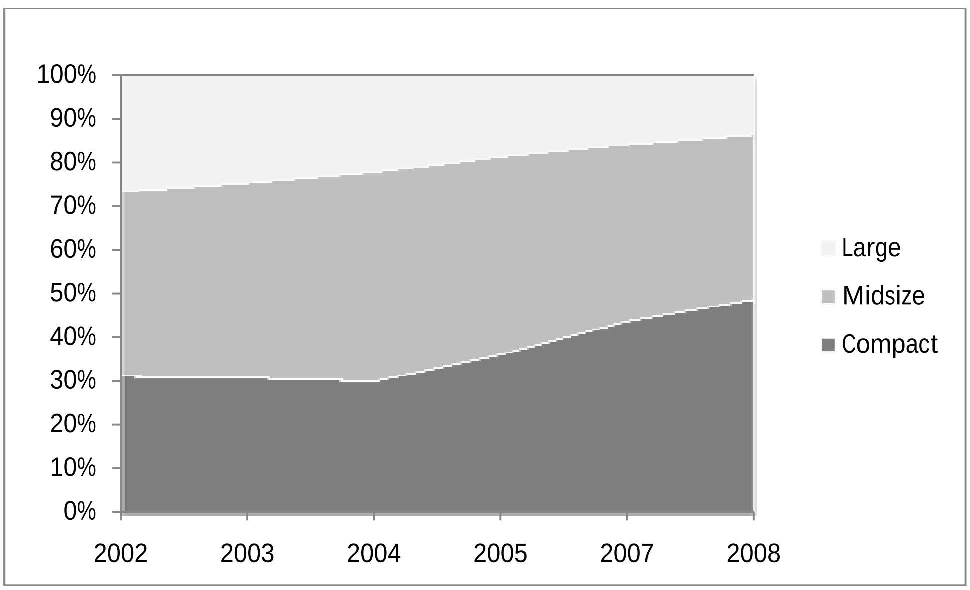


Figure E.16: SUV Sales by Subclass

Compact

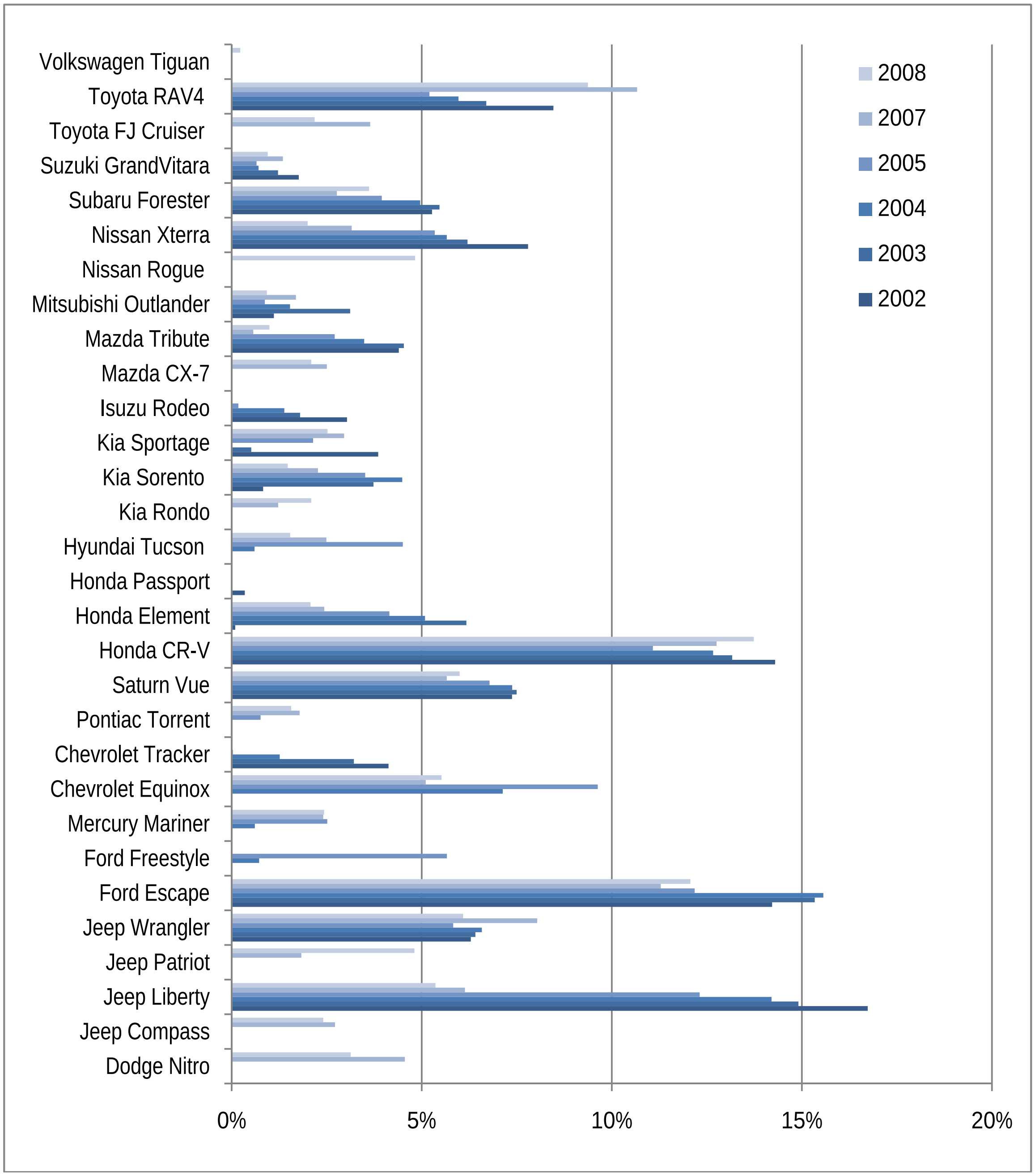


Figure E.17: Compact SUV Sales by Model Nameplate

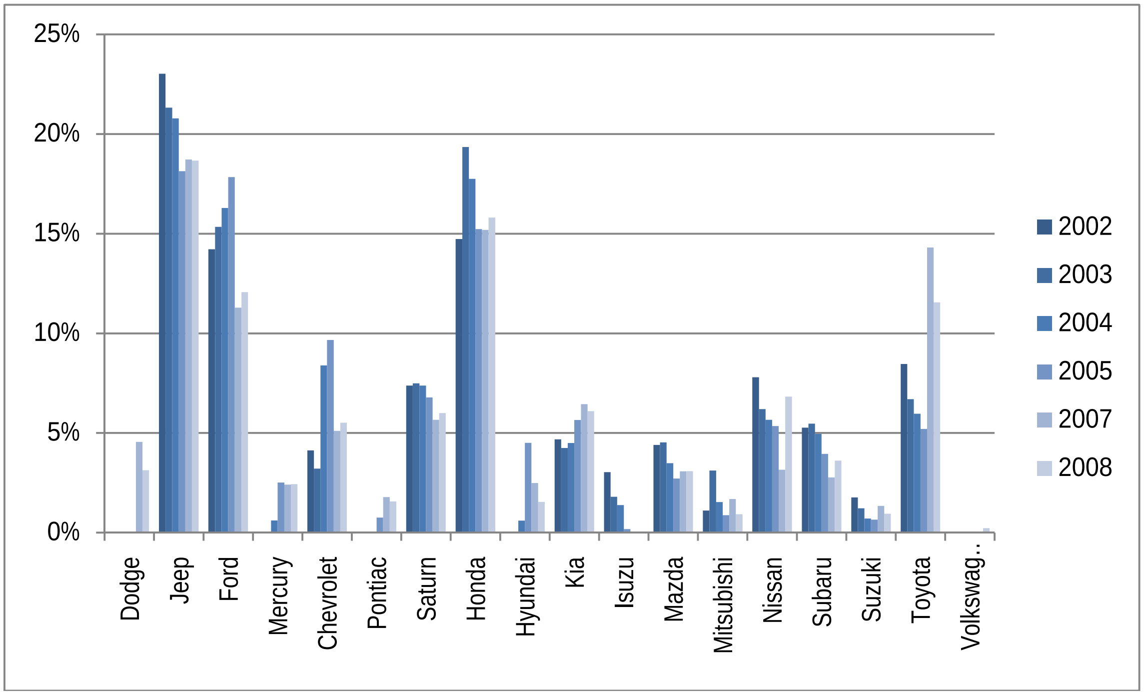


Figure E.18: Compact SUV Sales by Make

Table E.8: Percent of Yearly Compact SUV Sales by Make and Model

Compact SUV		Percent of yearly compact SUV sales						
Make	Model	2002	2003	2004	2005	2007	2008	Average
Dodge	Nitro	0.0	0.0	0.0	0.0	4.6	3.1	1.3%
Jeep	Compass	0.0	0.0	0.0	0.0	2.7	2.4	0.9%
Jeep	Liberty	16.7	14.9	14.2	12.3	6.1	5.4	11.6%
Jeep	Patriot	0.0	0.0	0.0	0.0	1.8	4.8	1.1%
Jeep	Wrangler	6.3	6.4	6.6	5.8	8.0	6.1	6.5%
Ford	Escape	14.2	15.3	15.6	12.2	11.3	12.1	13.4%
Ford	Freestyle	0.0	0.0	0.7	5.7	0.0	0.0	1.1%
Mercury	Mariner	0.0	0.0	0.6	2.5	2.4	2.4	1.3%
Chevrolet	Equinox	0.0	0.0	7.1	9.6	5.1	5.5	4.6%
Chevrolet	Tracker	4.1	3.2	1.3	0.0	0.0	0.0	1.4%
Pontiac	Torrent	0.0	0.0	0.0	0.8	1.8	1.6	0.7%
Saturn	Vue	7.4	7.5	7.4	6.8	5.7	6.0	6.8%
Honda	CR-V	14.3	13.2	12.7	11.1	12.8	13.7	13.0%
Honda	Element	0.1	6.2	5.1	4.2	2.4	2.1	3.3%
Honda	Passport	0.3	0.0	0.0	0.0	0.0	0.0	0.1%
Hyundai	Tucson	0.0	0.0	0.6	4.5	2.5	1.5	1.5%
Kia	Rondo	0.0	0.0	0.0	0.0	1.2	2.1	0.6%
Kia	Sorento	0.8	3.7	4.5	3.5	2.3	1.5	2.7%
Kia	Sportage	3.9	0.5	0.0	2.1	3.0	2.5	2.0%
Isuzu	Rodeo	3.0	1.8	1.4	0.2	0.0	0.0	1.1%
Mazda	CX-7	0.0	0.0	0.0	0.0	2.5	2.1	0.8%
Mazda	Tribute	4.4	4.5	3.5	2.7	0.6	1.0	2.8%
Mitsubishi	Outlander	1.1	3.1	1.5	0.9	1.7	0.9	1.5%
Nissan	Rogue	0.0	0.0	0.0	0.0	0.0	4.8	0.8%
Nissan	Xterra	7.8	6.2	5.7	5.3	3.2	2.0	5.0%
Subaru	Forester	5.3	5.5	5.0	3.9	2.8	3.6	4.3%
Suzuki	GrandVitara	1.8	1.2	0.7	0.7	1.3	0.9	1.1%
Toyota	FJ Cruiser	0.0	0.0	0.0	0.0	3.6	2.2	1.0%
Toyota	RAV4	8.5	6.7	6.0	5.2	10.7	9.4	7.7%
Volkswagen	Tiguan	0.0	0.0	0.0	0.0	0.0	0.2	0.0%

Midsize

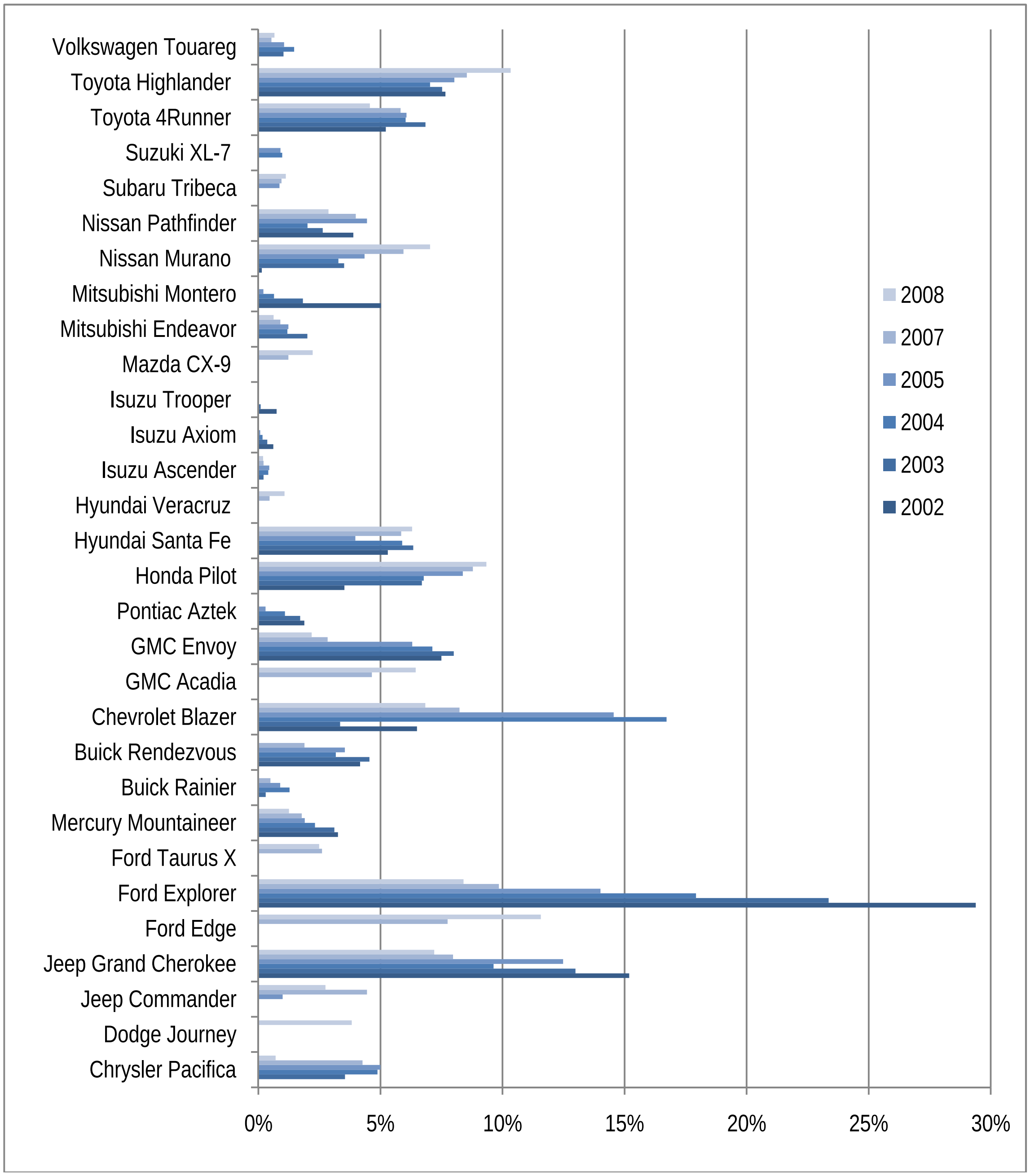


Figure E.19: Midsize SUVs Sales by Model Nameplate

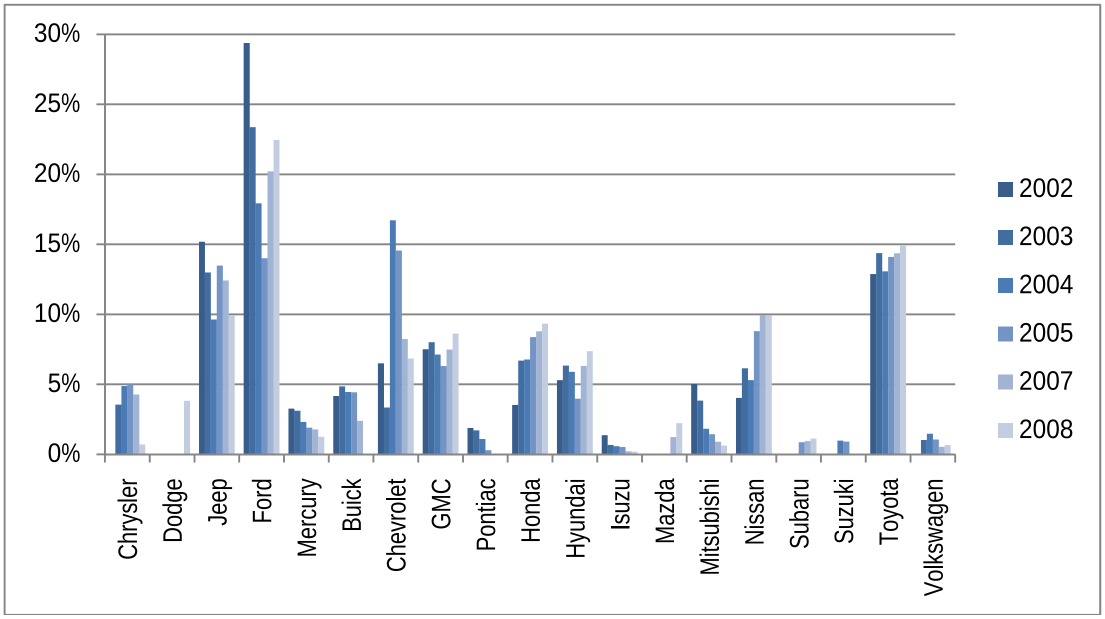


Figure E.20: Midsize SUV Sales by Make

Table E.9: Percent of Yearly Midsize SUV Sales by Make and Model

Midsize SUV		Percent of yearly midsize SUV sales						
Make	Model	2002	2003	2004	2005	2007	2008	Average
Chrysler	Pacifica	0.0	3.5	4.9	5.0	4.3	0.7	3.1%
Dodge	Journey	0.0	0.0	0.0	0.0	0.0	3.8	0.6%
Jeep	Commander	0.0	0.0	0.0	1.0	4.4	2.7	1.4%
Jeep	Grand Cherokee	15.2	13.0	9.6	12.5	8.0	7.2	10.9%
Ford	Edge	0.0	0.0	0.0	0.0	7.8	11.6	3.2%
Ford	Explorer	29.4	23.4	17.9	14.0	9.9	8.4	17.2%
Ford	Taurus X	0.0	0.0	0.0	0.0	2.6	2.5	0.8%
Mercury	Mountaineer	3.3	3.1	2.3	1.9	1.8	1.3	2.3%
Buick	Rainier	0.0	0.3	1.3	0.9	0.5	0.0	0.5%
Buick	Rendezvous	4.2	4.5	3.2	3.5	1.9	0.0	2.9%
Chevrolet	Blazer	6.5	3.3	16.7	14.6	8.2	6.8	9.4%
GMC	Acadia	0.0	0.0	0.0	0.0	4.7	6.4	1.8%
GMC	Envoy	7.5	8.0	7.1	6.3	2.8	2.2	5.7%
Pontiac	Aztek	1.9	1.7	1.1	0.3	0.0	0.0	0.8%
Honda	Pilot	3.5	6.7	6.8	8.4	8.8	9.3	7.2%
Hyundai	Santa Fe	5.3	6.3	5.9	4.0	5.9	6.3	5.6%
Hyundai	Veracruz	0.0	0.0	0.0	0.0	0.5	1.1	0.3%
Isuzu	Ascender	0.0	0.2	0.4	0.4	0.2	0.2	0.2%
Isuzu	Axiom	0.6	0.4	0.2	0.1	0.0	0.0	0.2%
Isuzu	Trooper	0.7	0.1	0.0	0.0	0.0	0.0	0.1%
Mazda	CX-9	0.0	0.0	0.0	0.0	1.2	2.2	0.6%
Mitsubishi	Endeavor	0.0	2.0	1.2	1.2	0.9	0.6	1.0%
Mitsubishi	Montero	5.0	1.8	0.6	0.2	0.0	0.0	1.3%
Nissan	Murano	0.1	3.5	3.3	4.4	5.9	7.0	4.0%
Nissan	Pathfinder	3.9	2.6	2.0	4.5	4.0	2.9	3.3%
Subaru	Tribeca	0.0	0.0	0.0	0.9	0.9	1.1	0.5%
Suzuki	XL-7	0.0	0.0	1.0	0.9	0.0	0.0	0.3%
Toyota	4Runner	5.2	6.8	6.0	6.1	5.8	4.6	5.8%
Toyota	Highlander	7.7	7.5	7.0	8.0	8.5	10.3	8.2%
Volkswagen	Touareg	0.0	1.0	1.5	1.1	0.5	0.7	0.8%

Large

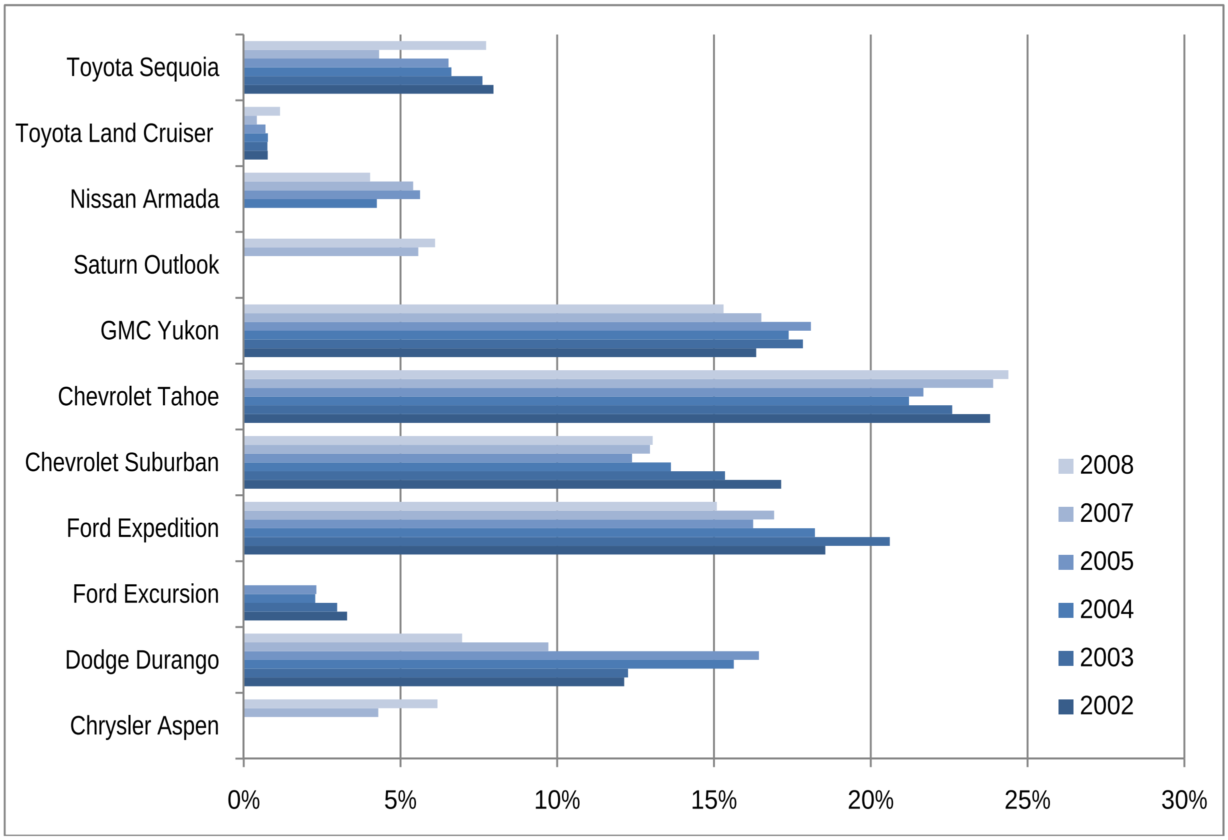


Figure E.21: Large SUV Sales by Model Nameplate

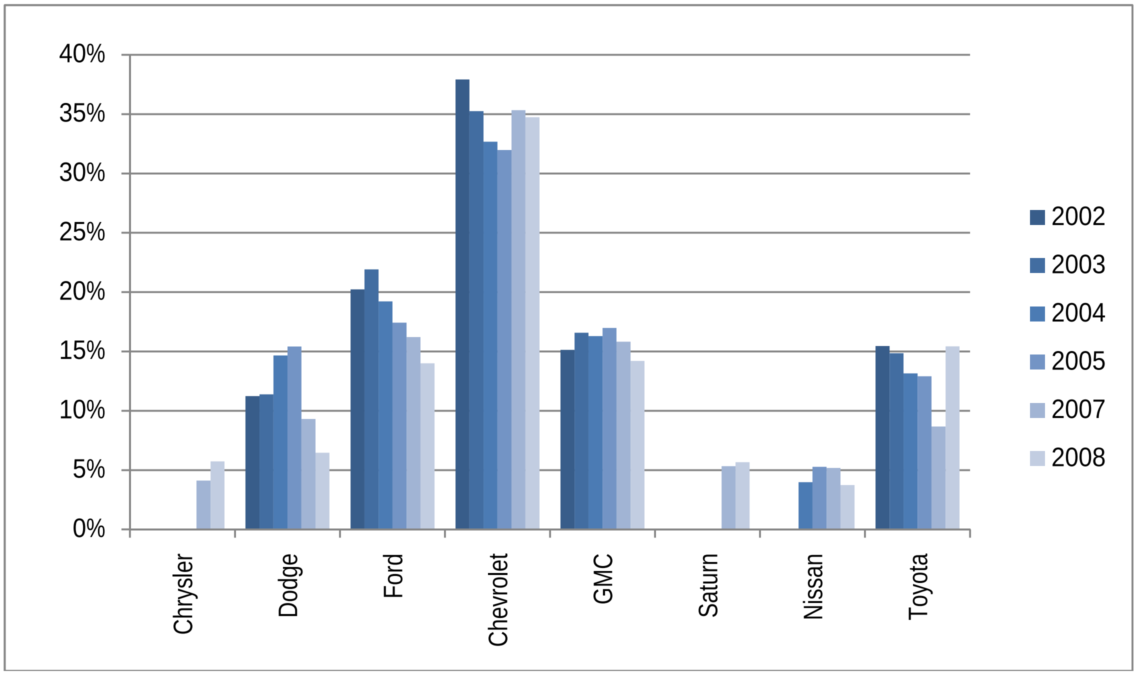


Figure E.22: Large SUV Sales by Make

Table E.10: Percent of Yearly Large SUV Sales by Make and Model

Large SUV		Percent of yearly Large SUV sales						
Make	Model	2002	2003	2004	2005	2007	2008	Average
Chrysler	Aspen	0.0	0.0	0.0	0.0	4.3	6.2	1.7%
Dodge	Durango	12.1	12.3	15.6	16.4	9.7	7.0	12.2%
Ford	Excursion	3.3	3.0	2.3	2.3	0.0	0.0	1.8%
Ford	Expedition	18.5	20.6	18.2	16.2	16.9	15.1	17.6%
Chevrolet	Suburban	17.1	15.3	13.6	12.4	13.0	13.0	14.1%
Chevrolet	Tahoe	23.8	22.6	21.2	21.7	23.9	24.4	22.9%
GMC	Yukon	16.3	17.8	17.4	18.1	16.5	15.3	16.9%
Saturn	Outlook	0.0	0.0	0.0	0.0	5.6	6.1	1.9%
Nissan	Armada	0.0	0.0	4.2	5.6	5.4	4.0	3.2%
Toyota	Land Cruiser	0.8	0.8	0.8	0.7	0.4	1.2	0.8%
Toyota	Sequoia	8.0	7.6	6.6	6.5	4.3	7.7	6.8%

Data for 12 months 2002-2005 and Jan-June 2007-2008

Appendix F: TxDOT Weigh in Motion Data Analysis

Vehicle Counts

The 2006 traffic survey data was aggregated across all 84 monitoring stations and analyzed.

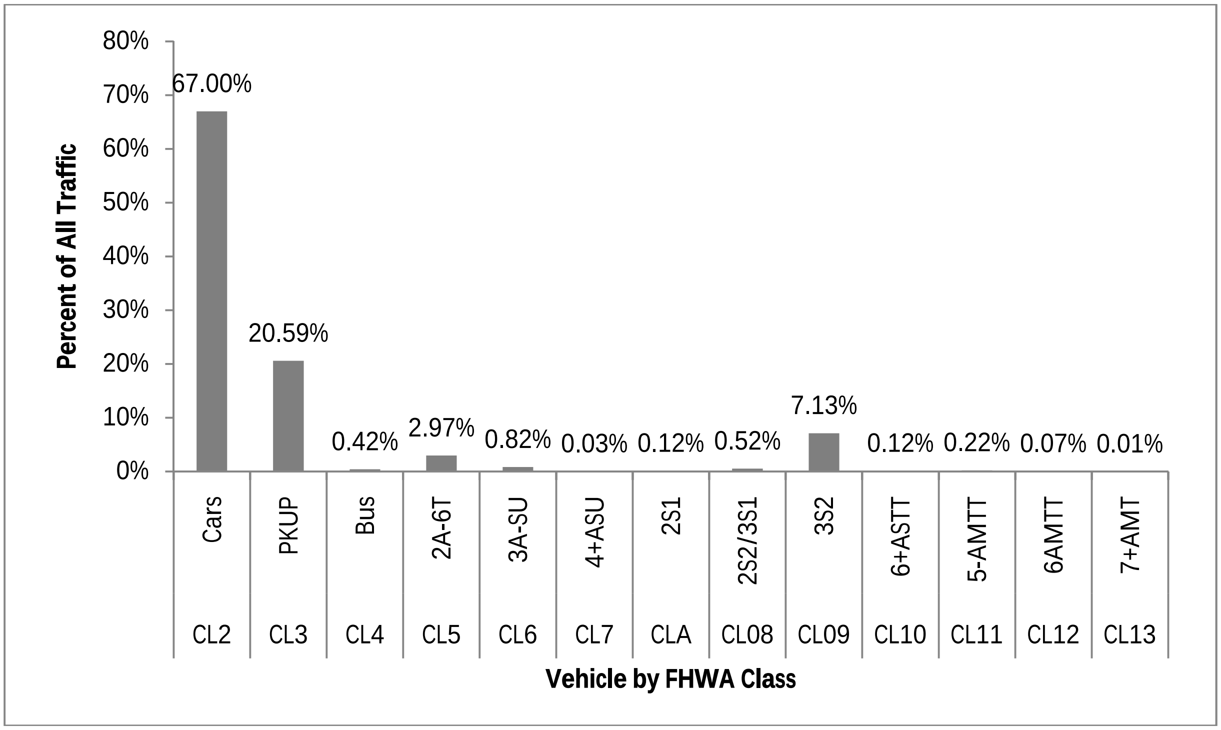
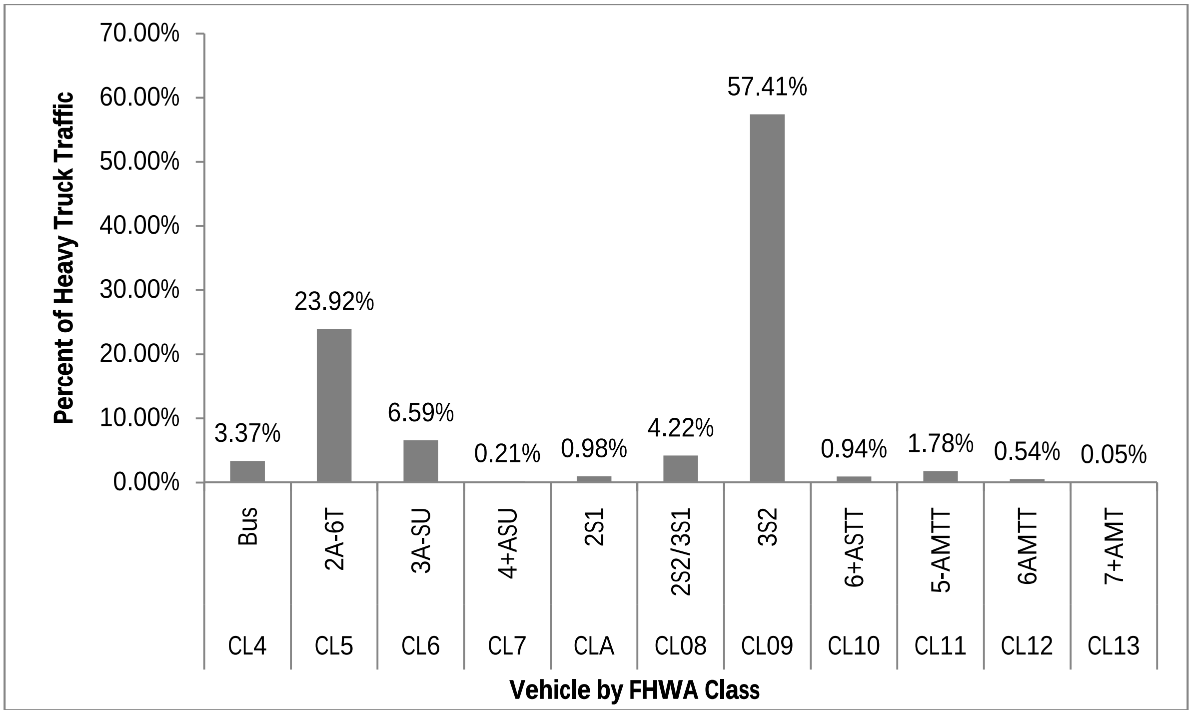


Figure F.1: Aggregate Vehicle Count traffic by FHWA type



Note: Only considering vehicles of FHWA class 4 and above (heavy trucks.)

Figure F.2: Aggregate Vehicle Count traffic by FHWA type

Weigh-in-Motion

FHWA Class 5 (2-Axle 6-Tire Truck)

Statistics are based on a 301311 single unit, 2-axle trucks recorded in the December 2006 Weigh-In-Motion testing (Card 7).

Note that the WIM data appears to cut off almost all lower-weight vehicles. No passenger vehicles were recorded in the Card7 data. There is also a sharp drop-off in vehicles recorded for weights under 7,000 lb. Though occasionally smaller weight amount are recorded (the minimum in this data set is 4,700 lb) it is uncertain what percentage of vehicle travel as these low weights was recorded.

Table F1: FHWA Class 5 (2-Axle 6-Tire Truck)

2ASU	Vehicle Weight (lb)
Median	8300
Average	9277
St Dev	3832
Min	4700
Max	74900

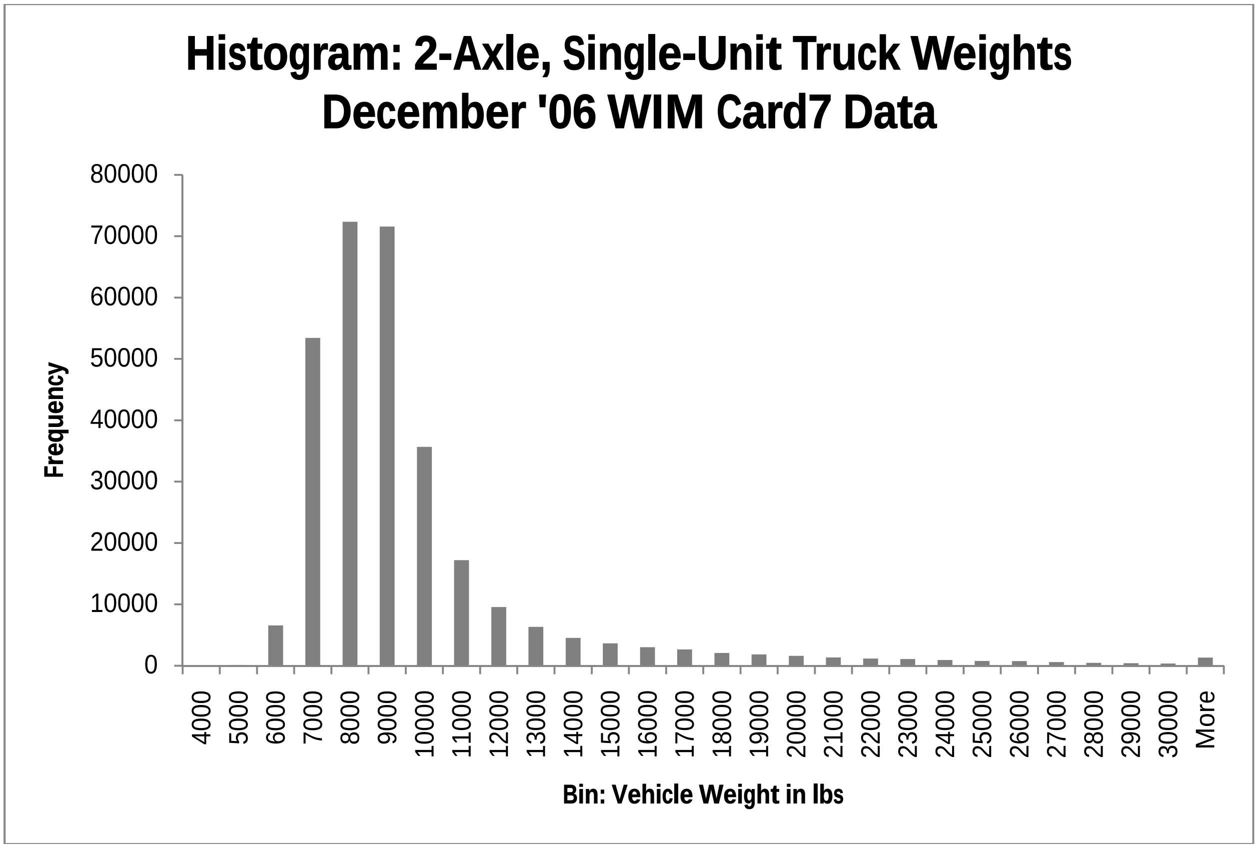


Figure F.3: 2-Axle, Singlue-Unit Truck Weights

FHWA Class 6 (3-Axle, Single Unit Truck)

Statistics are based on a 43073 single-unit, 3-axle trucks recorded in the December 2006 Weigh-In-Motion testing (Card 7).

Table F2: FHWA Class 6 (3-Axle, Single Unit Truck)

3ASU	Vehicle Weight (lb)
Median	35000
Average	35000
St Dev	15512
Max	60000
Min	10000

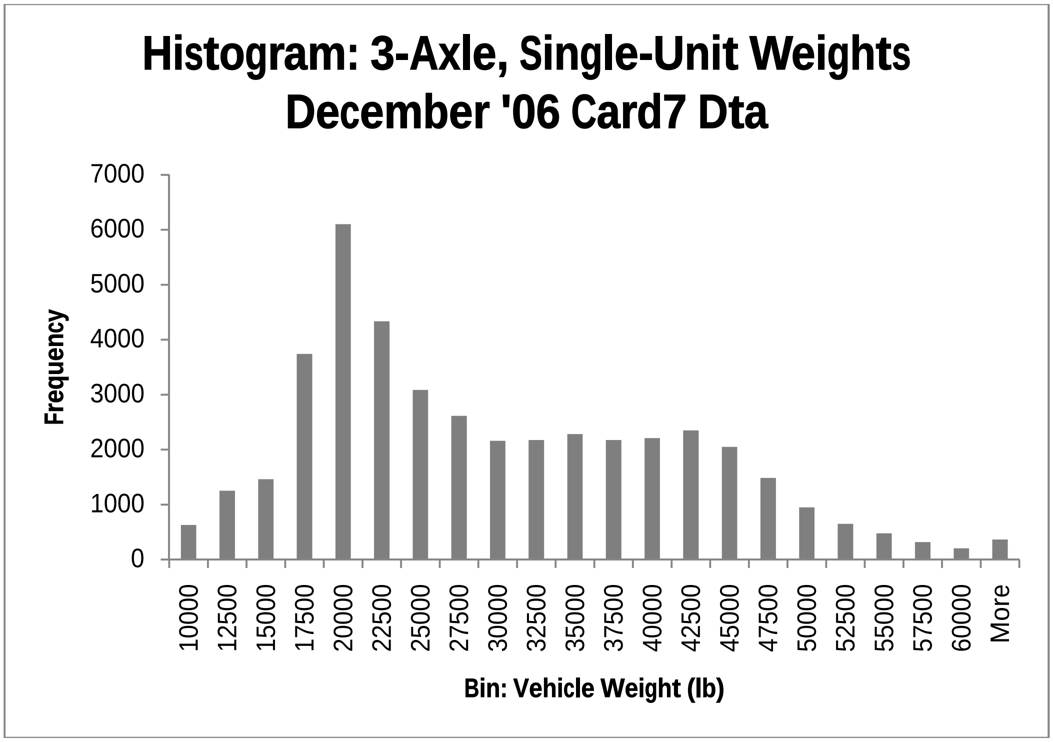


Figure F.4: 3-Axle, Single Unit Weights

FHWA Class 9 (5-axle Tractor-Trailer)

Data entries pertaining to 5-axle tractor/trailers were extracted from Card 7 Weigh-in-Motion data from 2006. This data was analyzed to determine basic statistical properties. Data from 4 months; January, April, October, and November; is shown below. This was used to determine an approximate cubed-out weight of 56000lb.

Table F3: FHWA Class 9 (5-Axle, Tractor-Trailer)

January 2006	
# Data Points	1015065
	Weight (lbs)
Average	56476
Median	57200
Mode	75400

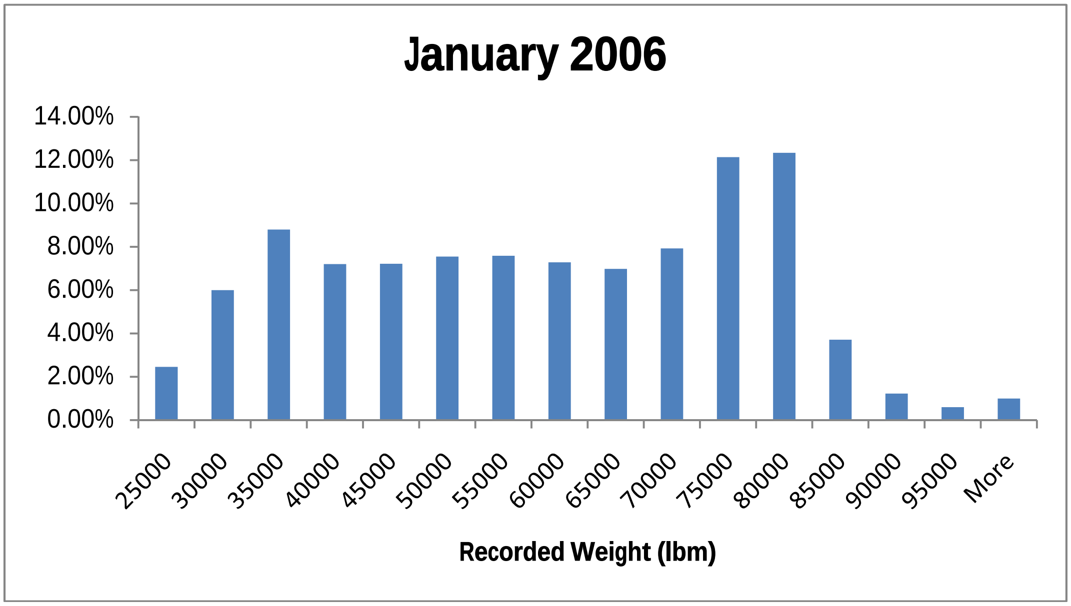


Figure F.5: 2006 Weigh-in-Motion data for class 9 trucks, January

Weigh-in-Motion Data: Aggregate for all vehicle types, by station

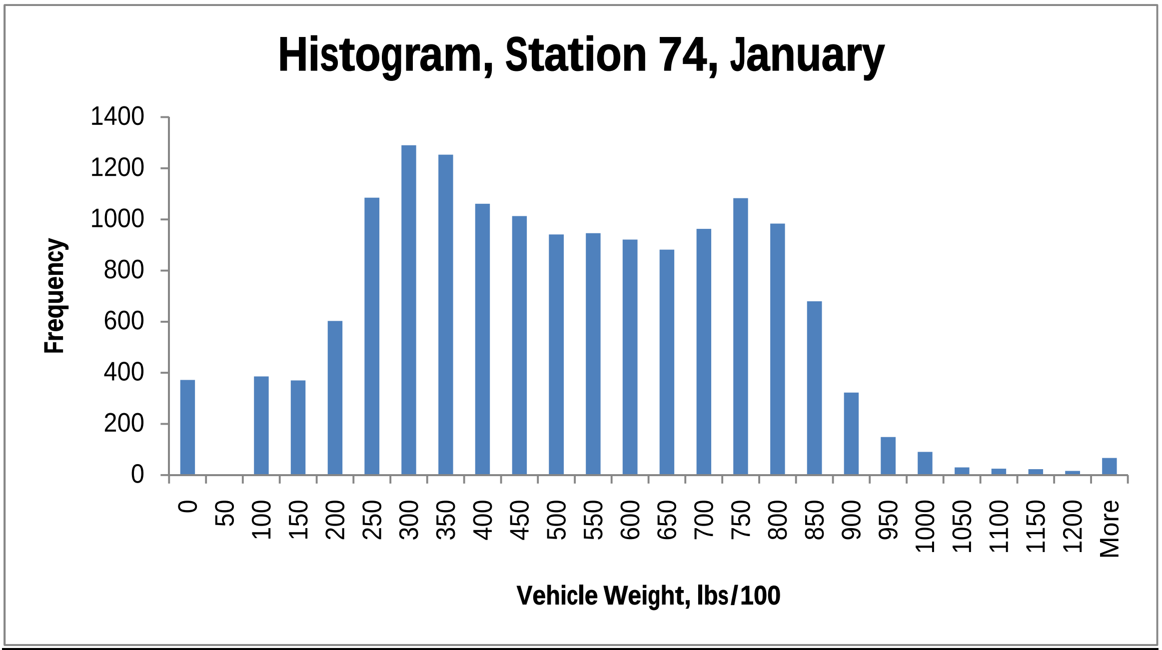


Figure F.6: 2006 Weigh-in-Motion data for class 9 trucks, Station 74, January

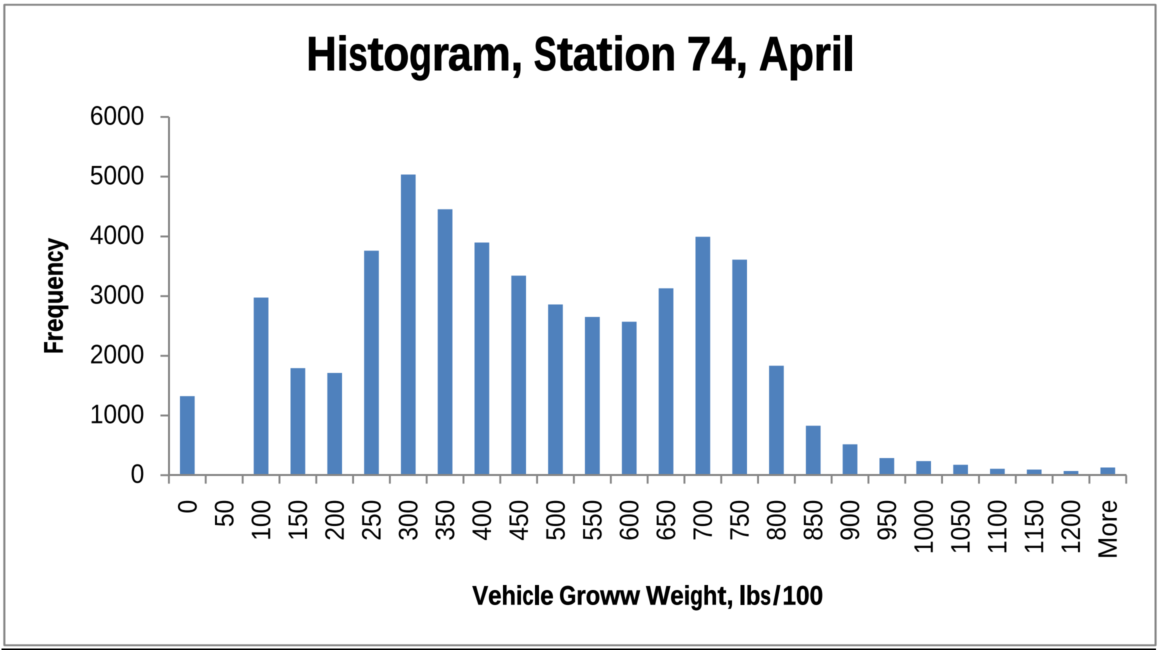


Figure F.7: 2006 Weigh-in-Motion data for class 9 trucks, Station 74, April

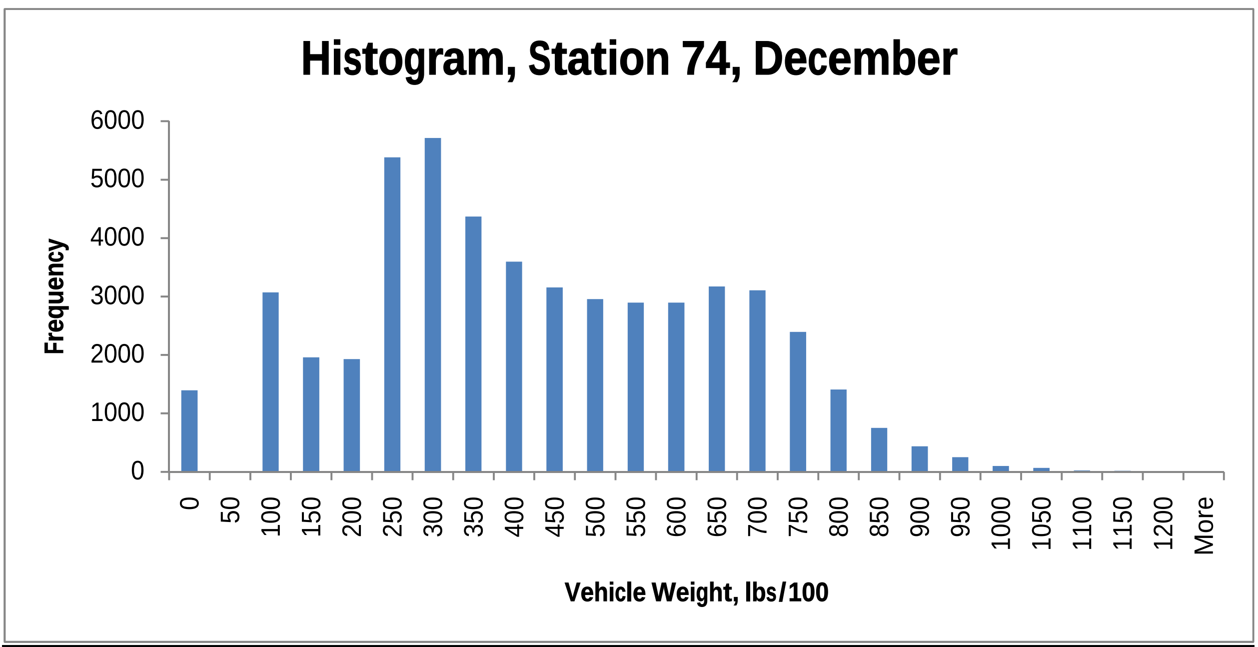


Figure F.8: 2006 Weigh-in-Motion data for class 9 trucks, Station 74, December

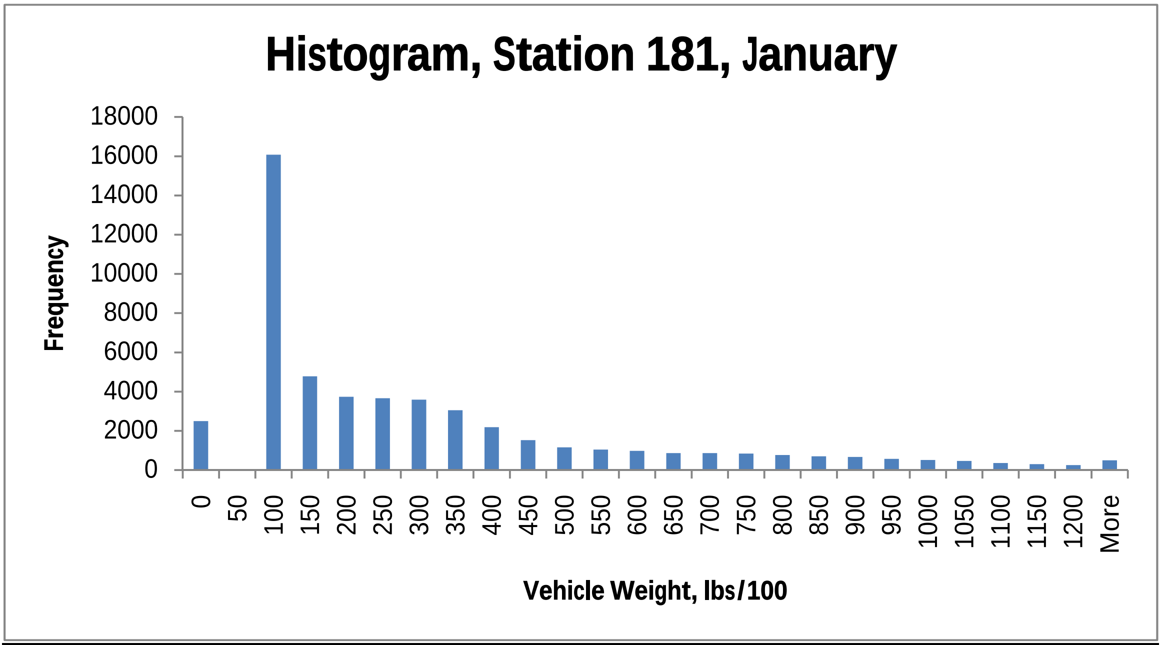


Figure F.9: 2006 Weigh-in-Motion data for class 9 trucks, Station 181, January

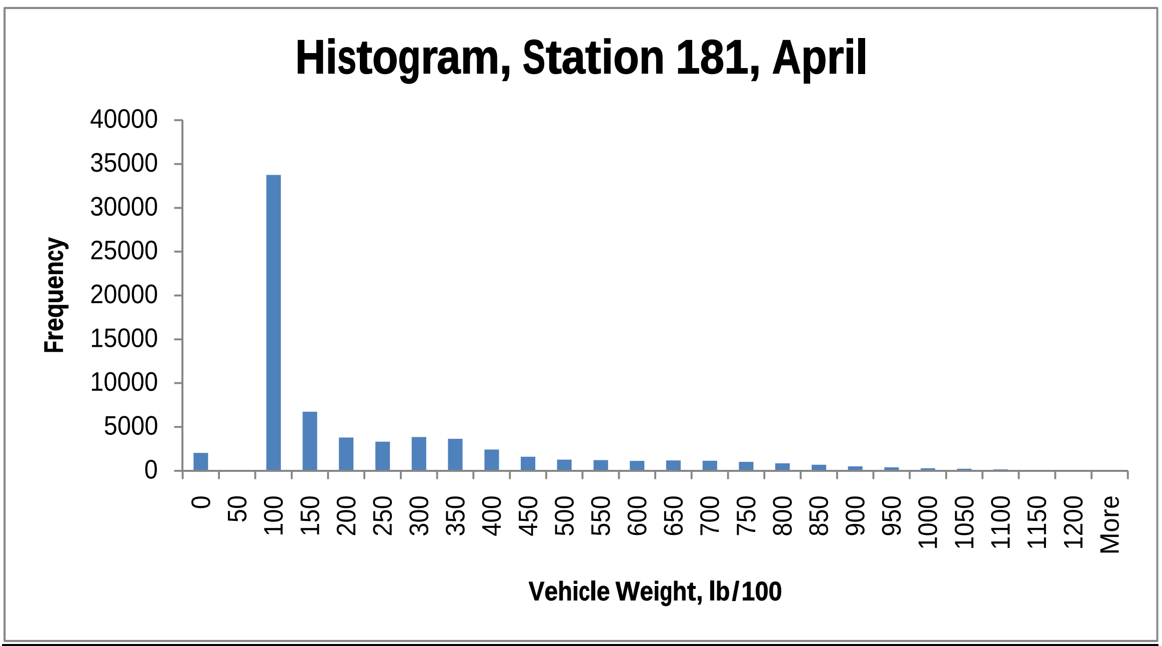


Figure F.10: 2006 Weigh-in-Motion data for class 9 trucks, Station 181, April

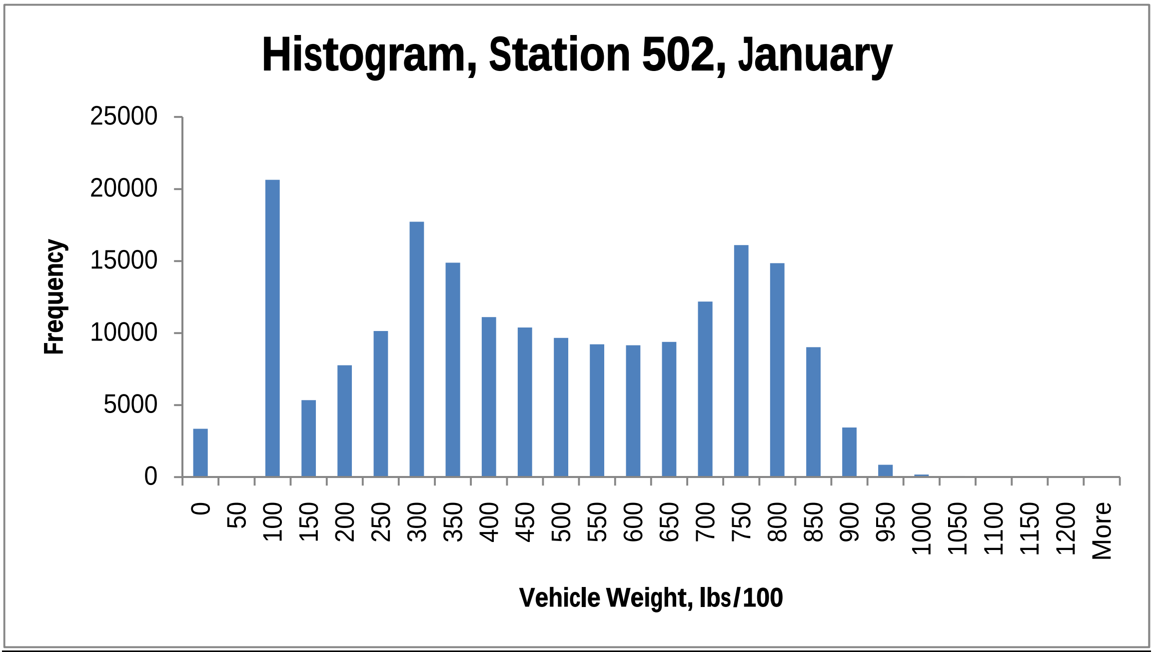


Figure F.11: 2006 Weigh-in-Motion data for class 9 trucks, Station 502, January

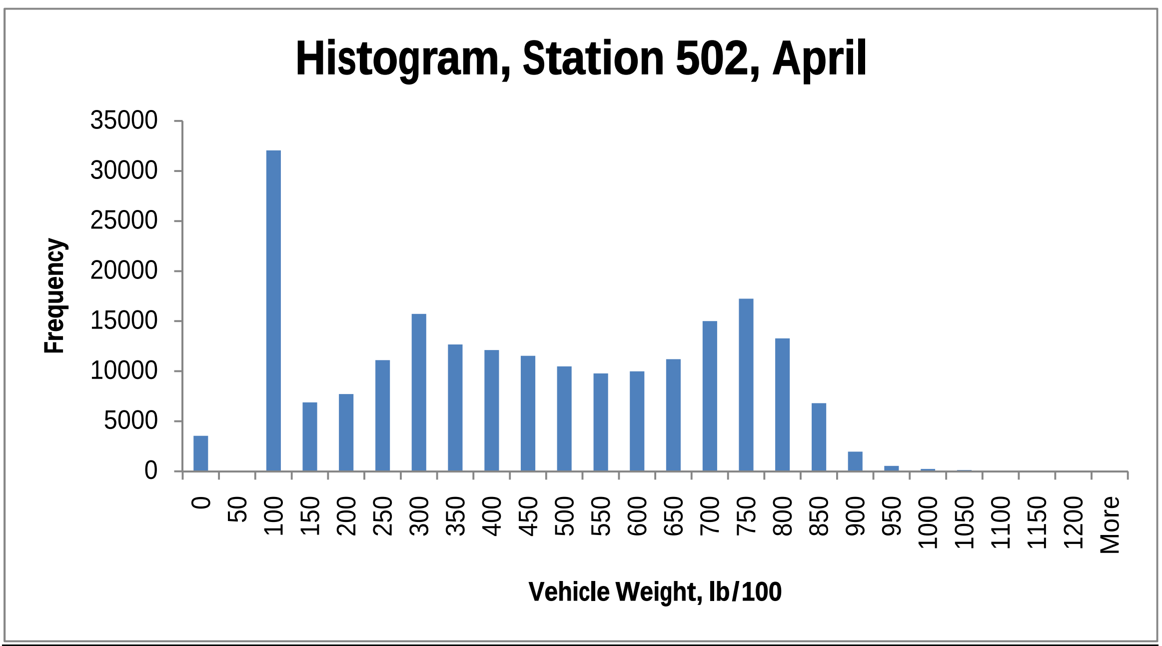


Figure F.12: 2006 Weigh-in-Motion data for class 9 trucks, Station 502, April

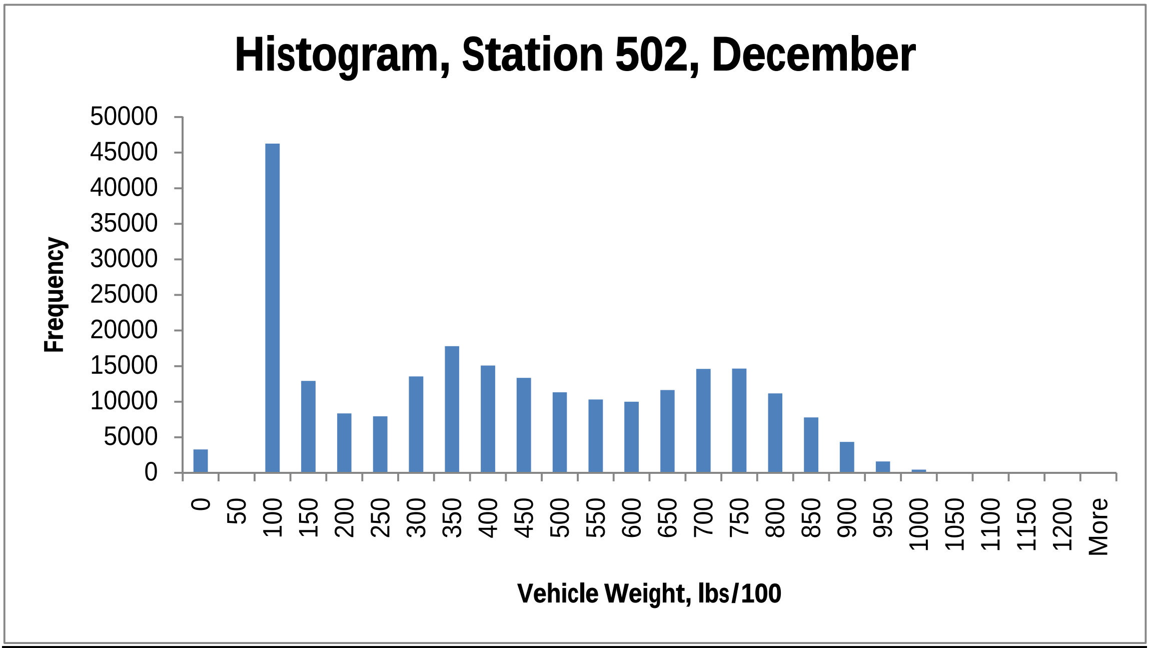


Figure F.13: 2006 Weigh-in-Motion data for class 9 trucks, Station 502, December

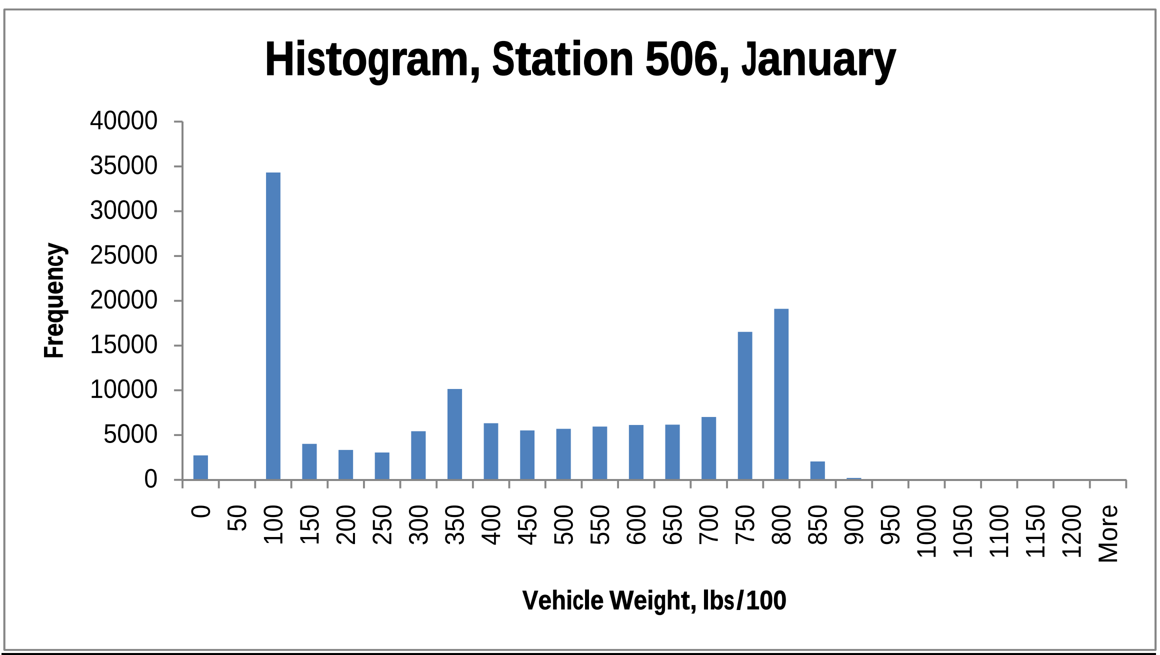


Figure F.14: 2006 Weigh-in-Motion data for class 9 trucks, Station 506, January

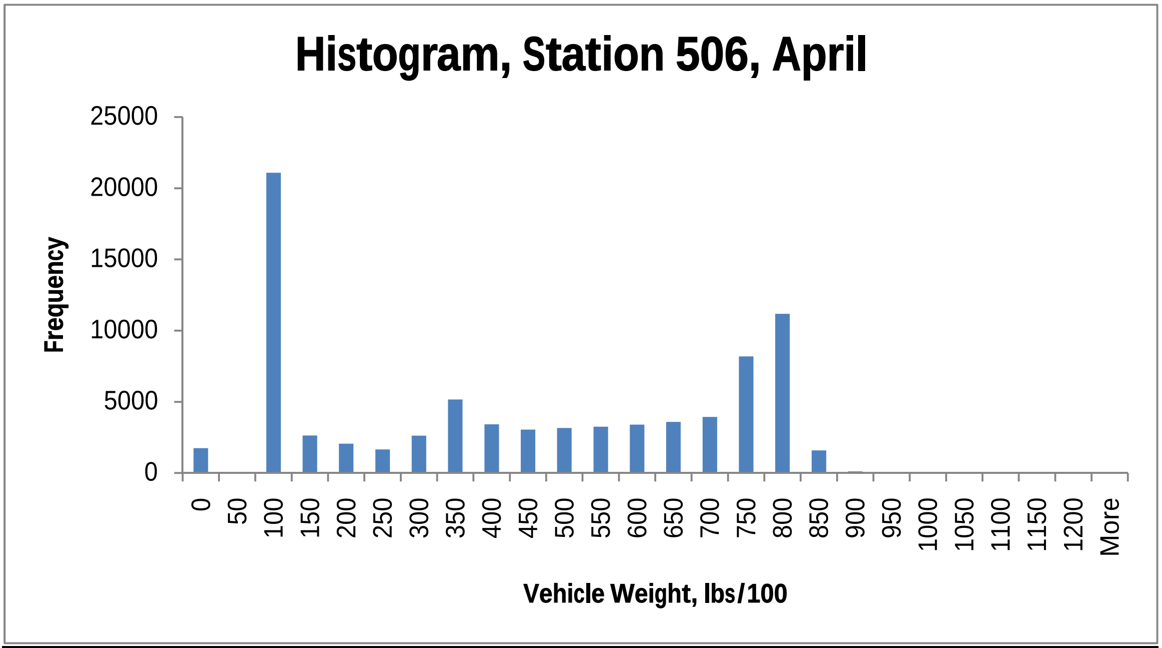


Figure F.15: 2006 Weigh-in-Motion data for class 9 trucks, Station 506, April

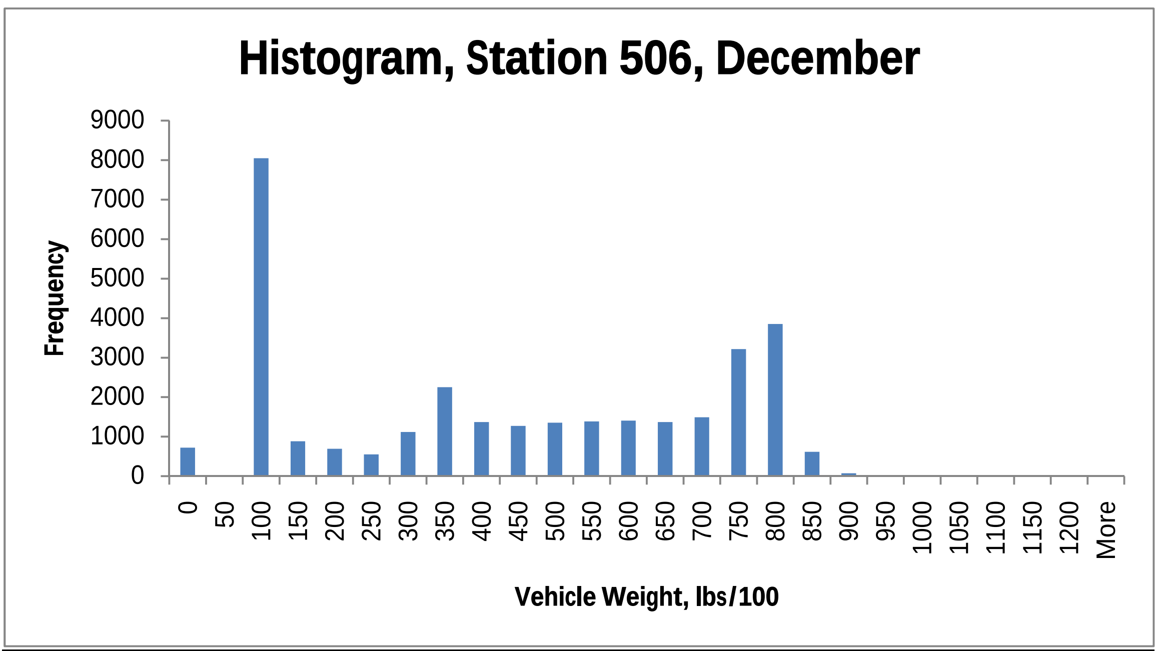


Figure F.16: 2006 Weigh-in-Motion data for class 9 trucks, Station 506, December

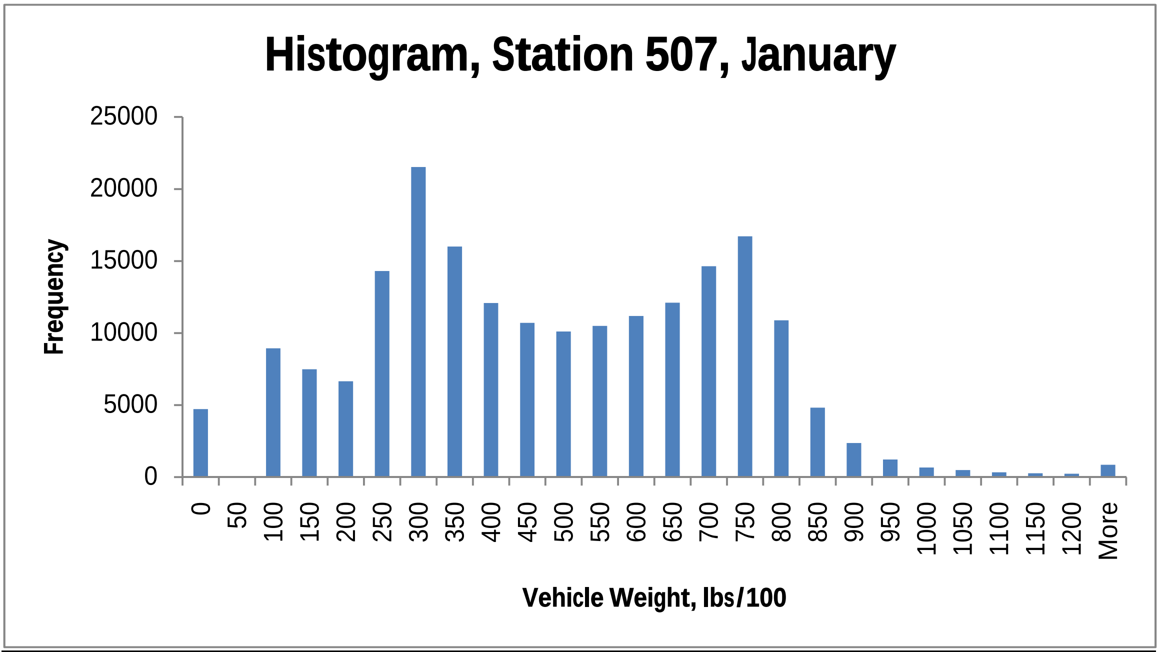


Figure F.17: 2006 Weigh-in-Motion data for class 9 trucks, Station 507, January

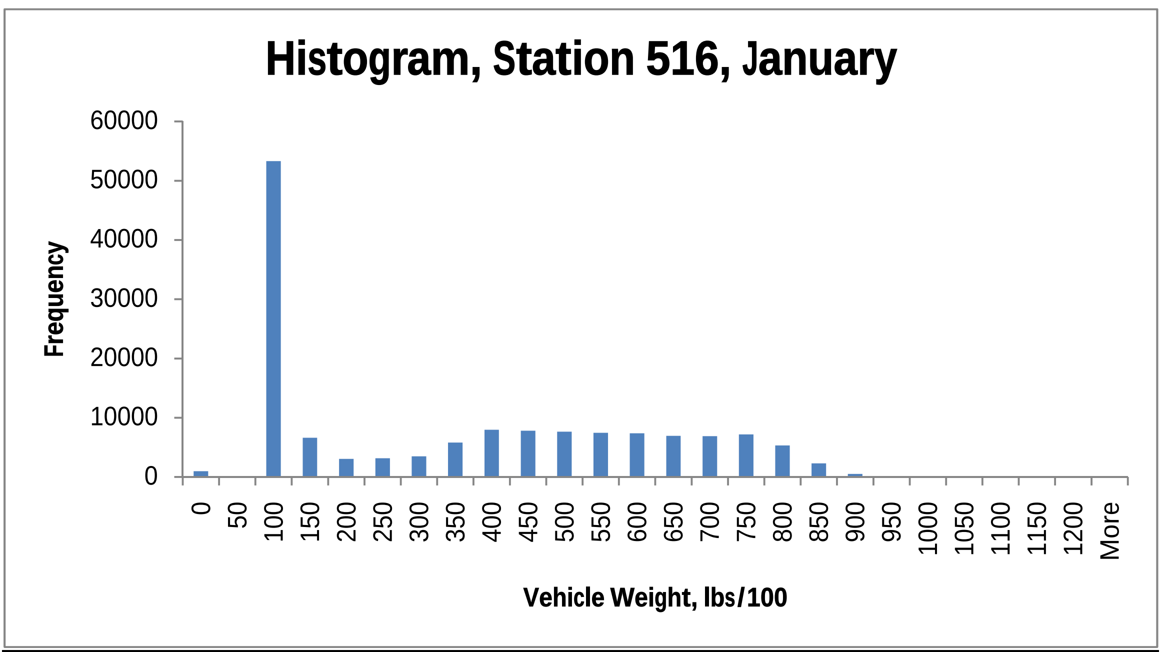


Figure F.18: 2006 Weigh-in-Motion data for class 9 trucks, Station 516, January

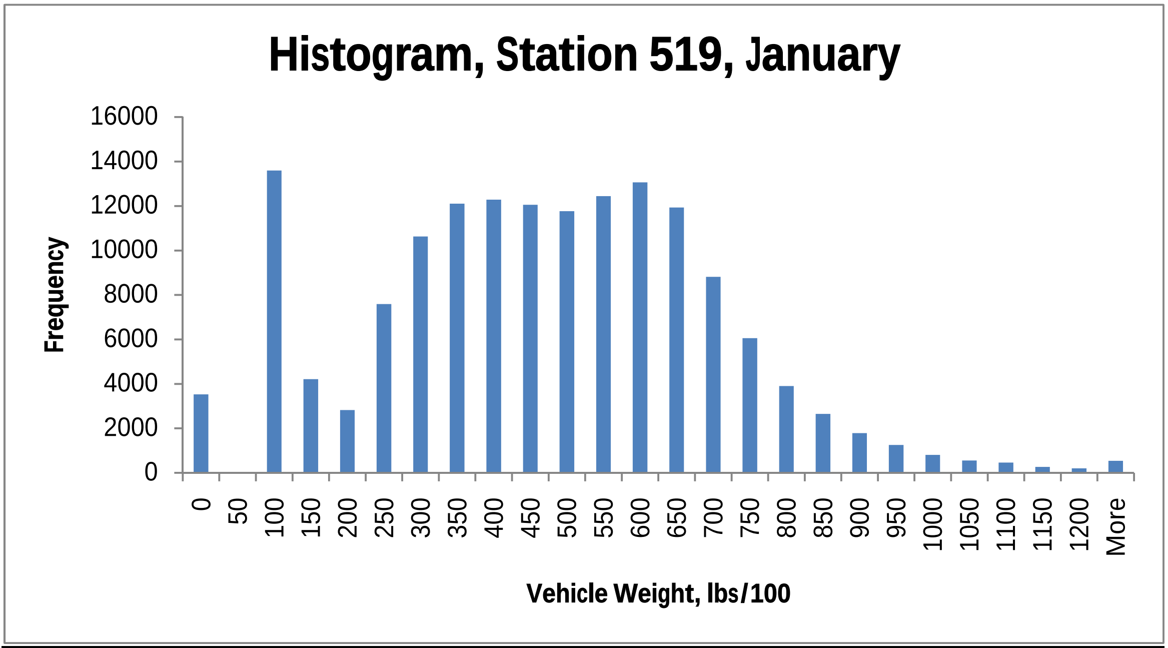


Figure F.19: 2006 Weigh-in-Motion data for class 9 trucks, Station 519, January

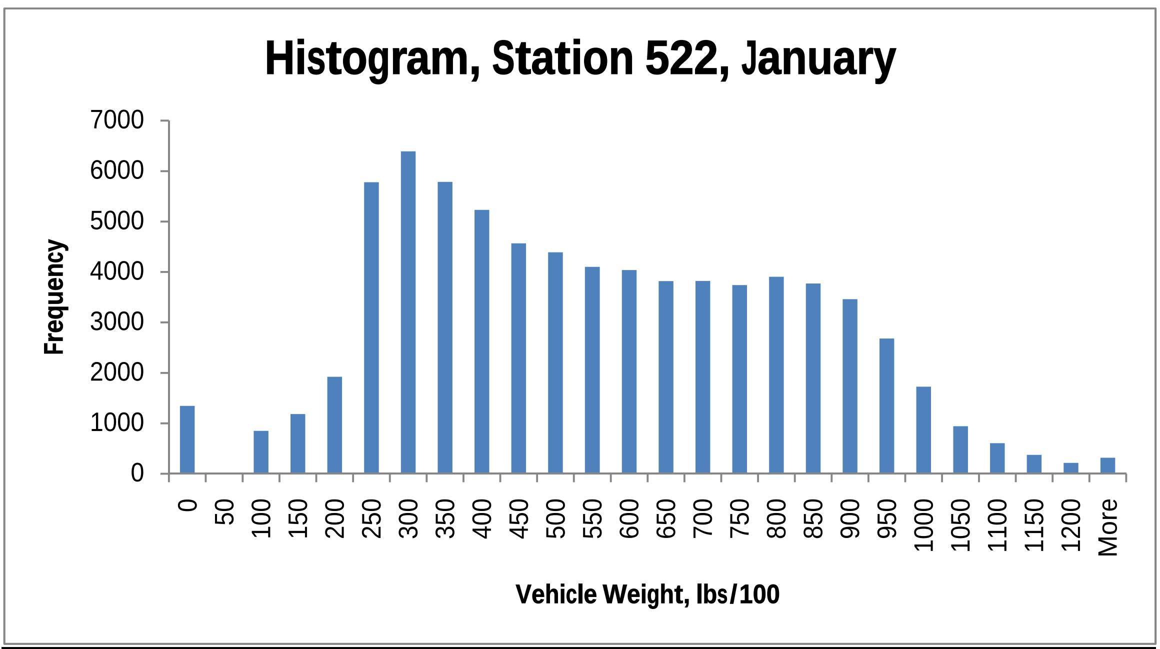


Figure F.20: 2006 Weigh-in-Motion data for class 9 trucks, Station 522, January

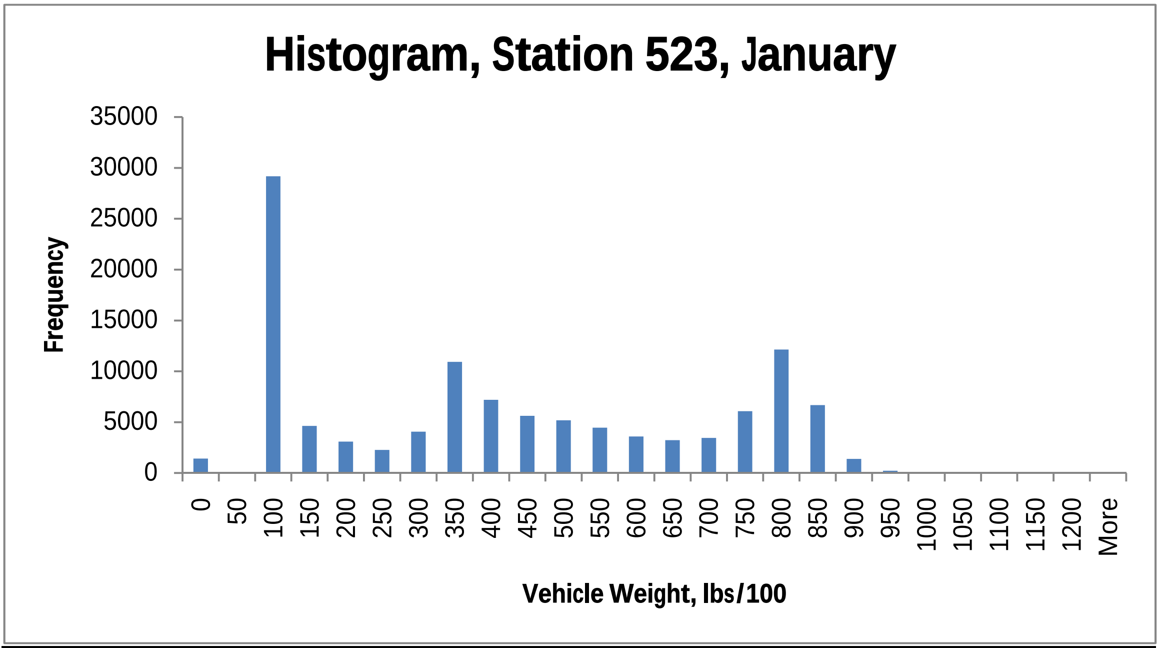


Figure F.21: 2006 Weigh-in-Motion data for class 9 trucks, Station 523, January

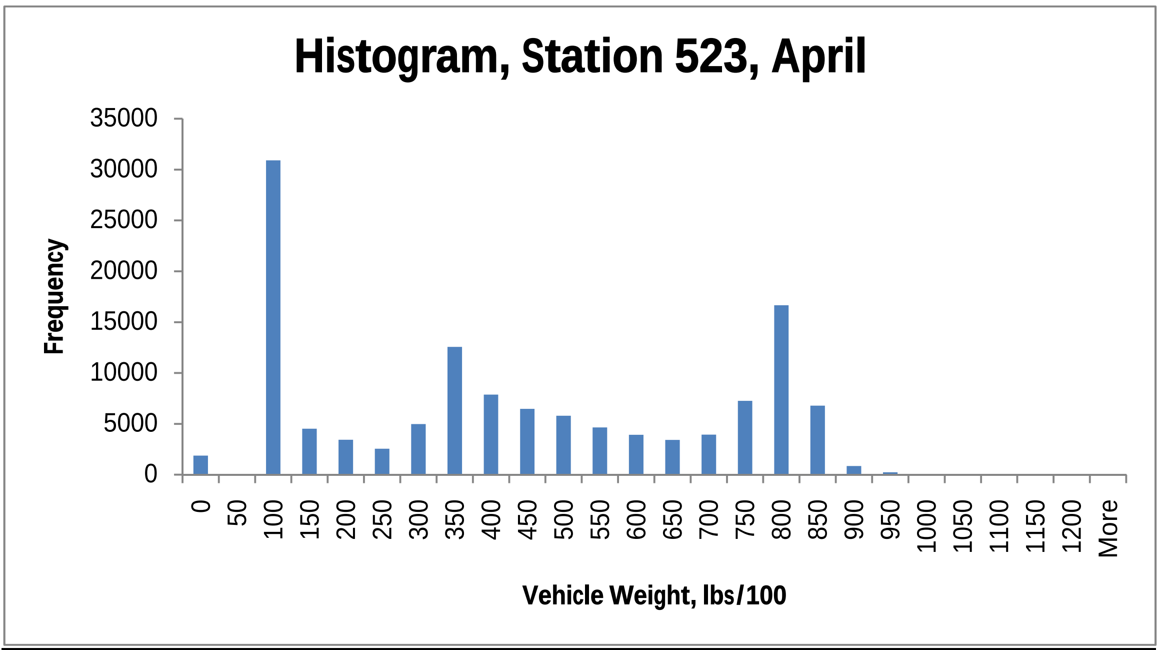


Figure F.22: 2006 Weigh-in-Motion data for class 9 trucks, Station 523, April

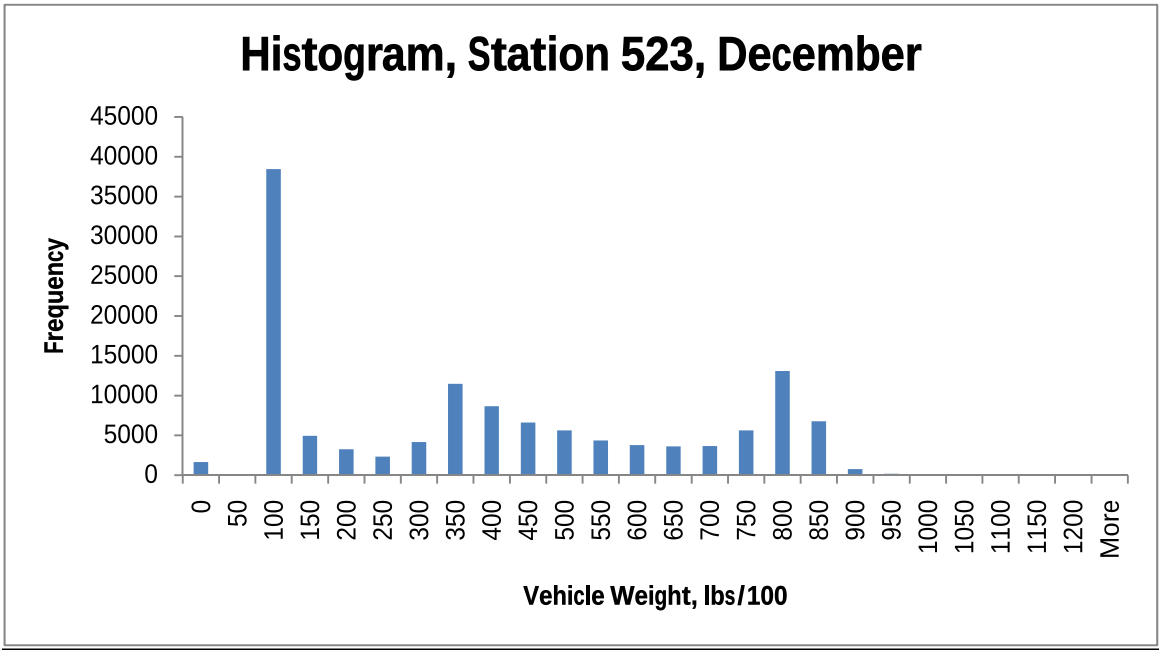


Figure F.23: 2006 Weigh-in-Motion data for class 9 trucks, Station 523, December

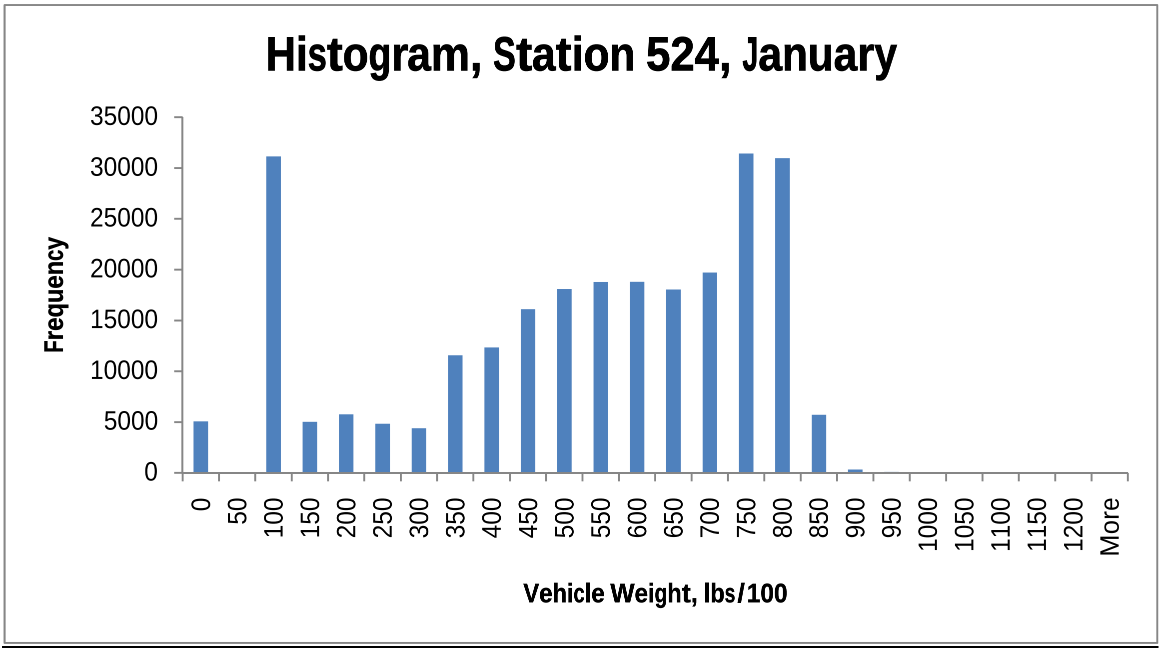


Figure F.24: 2006 Weigh-in-Motion data for class 9 trucks, Station 524, January

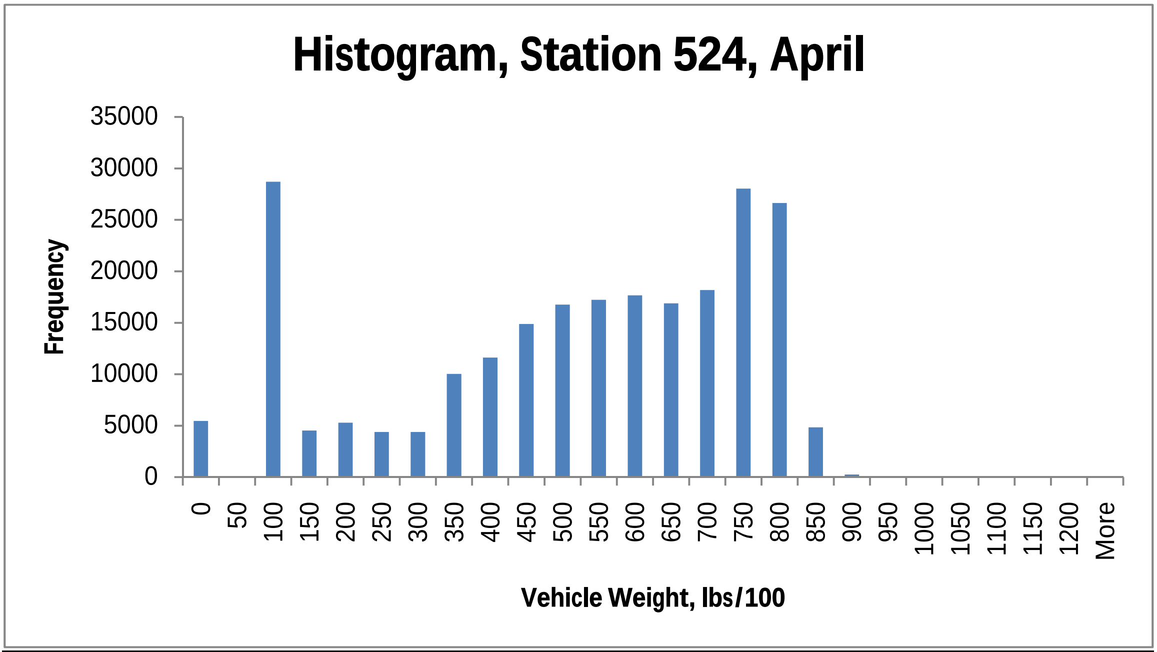


Figure F.25: 2006 Weigh-in-Motion data for class 9 trucks, Station 524, April

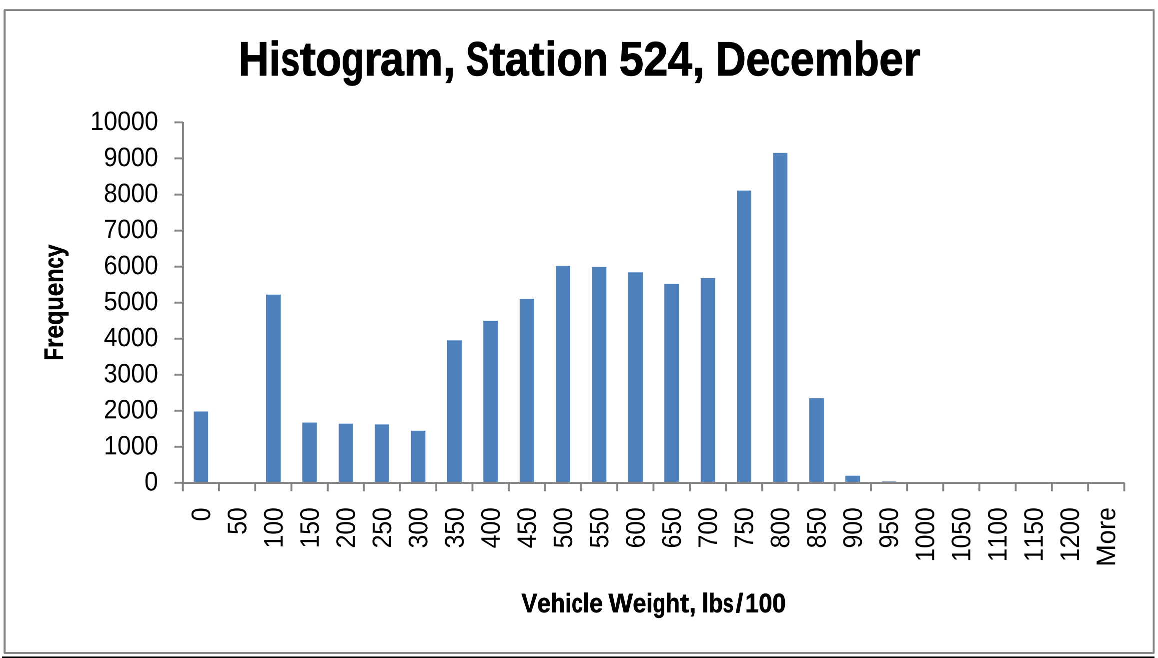


Figure F.26: 2006 Weigh-in-Motion data for class 9 trucks, Station 524, December

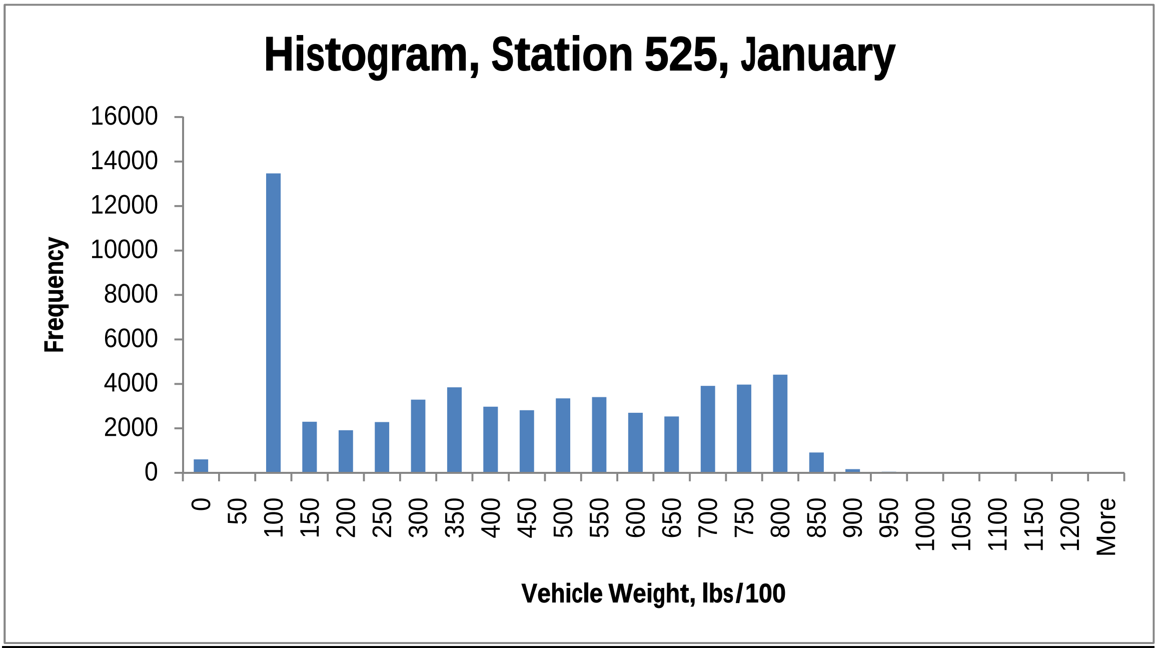


Figure F.27: 2006 Weigh-in-Motion data for class 9 trucks, Station 525, January

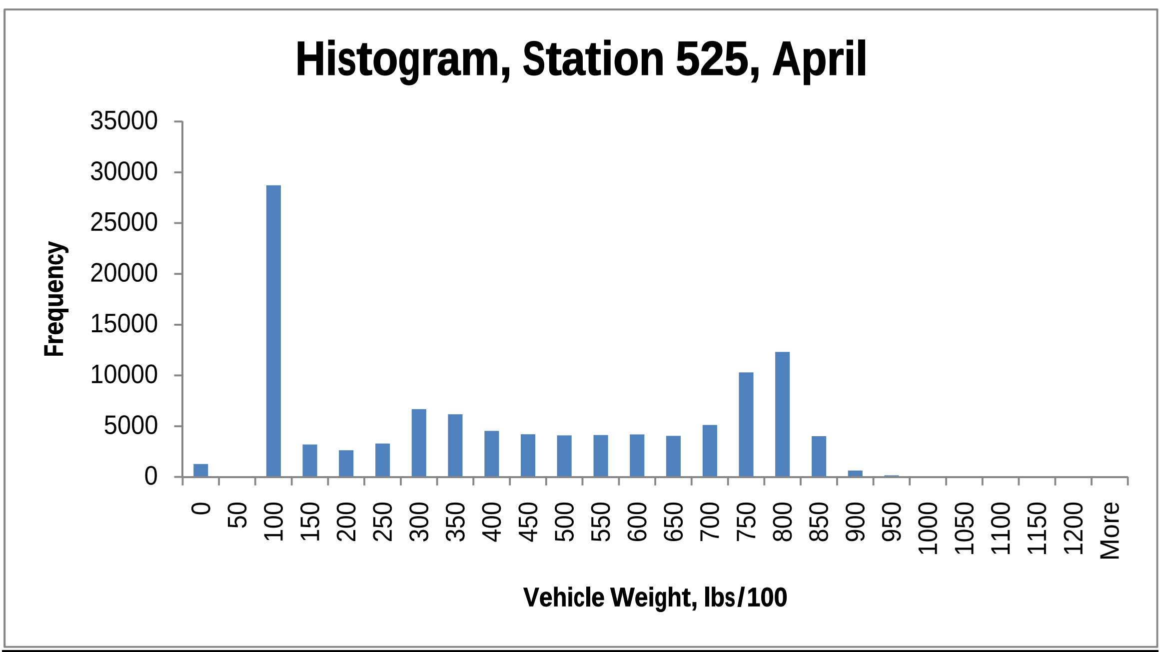


Figure F.28: 2006 Weigh-in-Motion data for class 9 trucks, Station 525, April

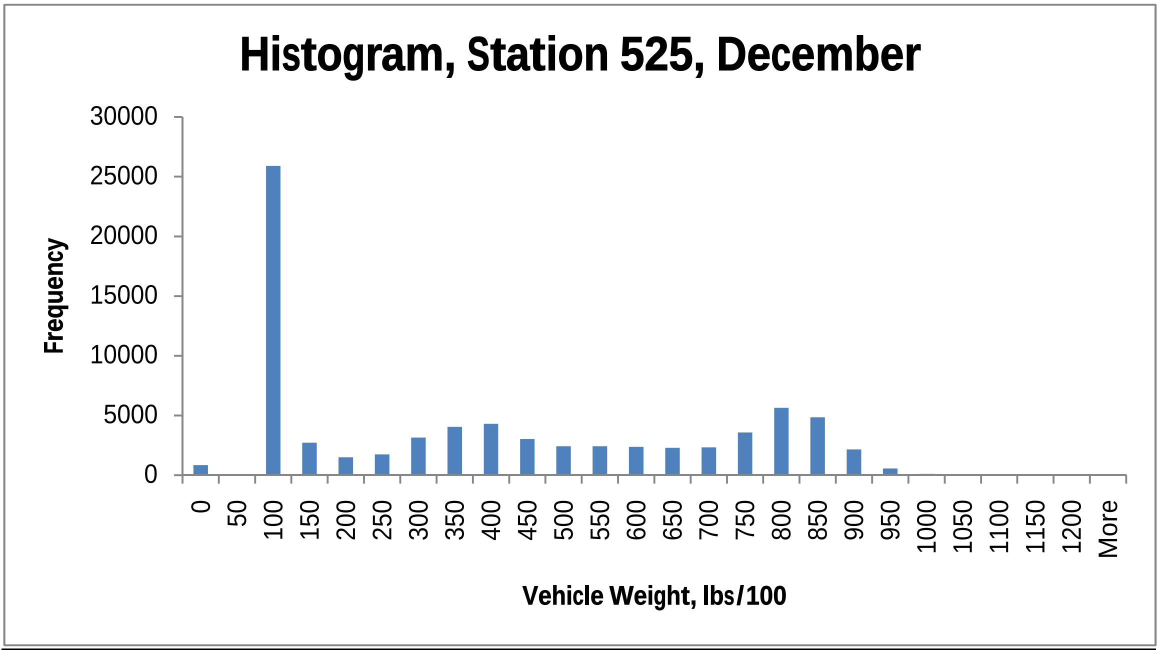


Figure F.29: 2006 Weigh-in-Motion data for class 9 trucks, Station 525, December

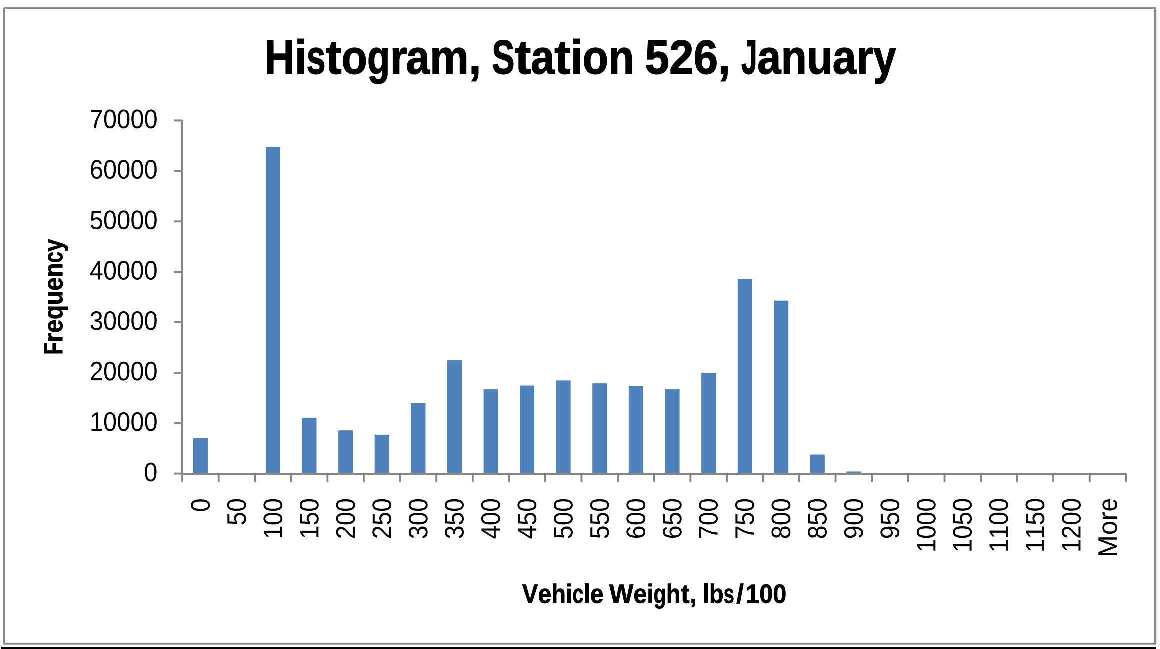


Figure F.30: 2006 Weigh-in-Motion data for class 9 trucks, Station 526, January

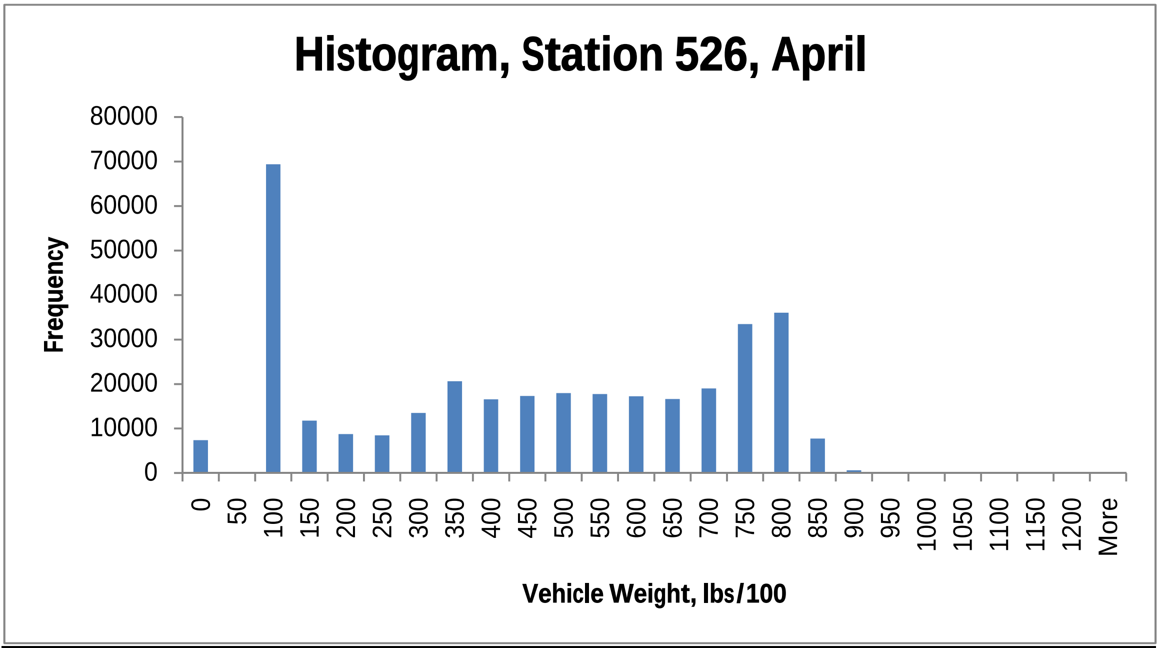


Figure F.30: 2006 Weigh-in-Motion data for class 9 trucks, Station 526, April

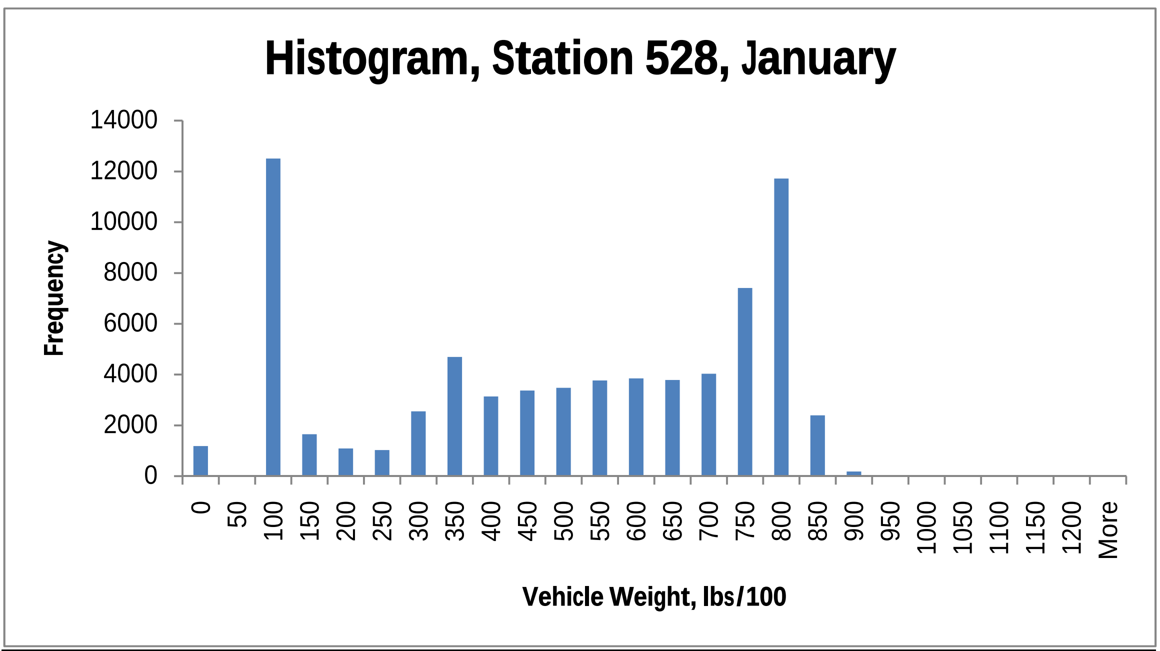


Figure F.31: 2006 Weigh-in-Motion data for class 9 trucks, Station 528, January

Appendix G: Drivetrain Models for Light-Duty and Heavy-Duty Vehicles

Drivetrain models for both light-duty and heavy-duty vehicles are discussed in this appendix. The initial models used for the performance and efficiency of a light-duty differential and transmission are discussed in Sections G.1 and G.2, respectively. Section G.3 covers the initial model used for the performance and efficiency of a light-duty engine. The initial models used for the performance and efficiency of a heavy-duty differential and transmission are discussed in Section G.4. Section G.5 covers the initial model used for the performance and efficiency of a heavy-duty engine.

G.1. Model for the Torque Multiplication and Efficiency of a Light-Duty Differential

The differential model consists of two aspects: the gear ratio and the efficiency of the differential. The differential efficiency model for the initial fuel economy simulation is (Matthews, 2009):

$$\eta_d = 0.6652 + 0.003732S - 0.0000106S^2 \qquad \text{G.1}$$

where η_d is the dimensionless differential efficiency and S is the vehicle speed in km/h. Equation G.1 is valid for vehicle speeds below 150 km/h, above which η_d = 0.987. This model is based upon vehicles from the 1980s. A differential efficiency model that is suitable for current vehicles will be generated during the modification phase of TxDOT Project 0-5974. In the current version of the vehicle-specific model, the user is to supply the differential gear ratio, which is used to calculate the transmission output shaft speed given the vehicle speed. This relationship is:

$$N_{t,output} = N_{driven\ tires/wheels} \cdot G_d = \frac{S \cdot G_d}{2\pi R_T} \qquad \text{G.2}$$

where G_d is the gear ratio of the differential, S is the vehicle speed, R_T is the rolling radius of the "driven" tires, $N_{driven\ tires/wheels}$ is the rotational speed of the driven wheel/tire assemblies, and $N_{t,output}$ is the rotational speed of the driveshaft (the transmission output shaft).

Given vehicle speed, S, the rolling radius of the tires, and the differential gear ratio, one can calculate the rotational speed of the driveshaft via Equation G.2. Also, as explained in Chapter 5, one can calculate the motive torque required at the tire-road interface (τ_{road}) in order for the vehicle to travel at speed S. The differential provides a torque multiplication from its input shaft (the driveshaft) to the axles and wheels/tires. Thus, the torque required at the differential input (which is the torque required at the transmission output) can be calculated via:

$$\tau_{trans\ output} = \frac{\tau_{road}}{G_d \eta_d} \qquad \text{G.3}$$

where the differential efficiency is obtained via Equation G.1.

G.2. Model for the Torque Multiplication and Efficiency of a Light-Duty Transmission

In order to predict the fuel economy of a specific vehicle, it is necessary to account for 1) the performance of, and energy losses in, the transmission, and 2) the gear shift strategy. The second of these is required in order to simulate which transmission gear is engaged at each specific vehicle speed. The transmission model used for the initial development of the vehicle-specific fuel economy model is discussed in this section.

The DOT data base revealed that 86% of the light-duty vehicles offered for sale in the U.S. during model year 2008 had some sort of automatic transmission. However, simulating an automatic transmission is quite complicated. Therefore, a reasonably accurate model for a manual transmission was developed, and the various types of automatics were scaled from the efficiency of the manual.

A manual transmission consists of two co-linear shafts, the input and output shaft, and a parallel shaft that is called the layshaft. A gear on the input shaft continuously drives a mating gear on the layshaft. This turns the layshaft at a slower rotational speed than the input shaft, which is rotating at engine rpm whenever the clutch is fully engaged. The decrease in speed of the layshaft relative to the input shaft is accompanied by an increase in torque, but there is inefficiency in this torque multiplication.

Several other gears are also rotating on the layshaft: there are 4 "drive" gears if it's a 4-speed, 6 if it's a 6-speed, etc. Except in a very few cases, all of the gears on the layshaft continuously rotate at layshaft rpm. Each of these drive gears is rotating a mating gear on the output shaft. All of the gears on the output shaft "freewheel" except for the gear that is engaged by the vehicle's driver via the gear shift lever. The gear shift lever moves a "dog" that couples the selected gear on the output shaft to the output shaft, so that the selected gear rotates the output shaft, which can be stationary until a dog engages one of the output shaft gears. Thus, the rotational speed of the layshaft, $N_{layshaft}$, can be calculated from:

$$N_{layshaft} = N_{t,output} \cdot G_{l\text{-}o} = N_{driven\ tires/wheels} \cdot G_d \cdot G_{l\text{-}o} = \frac{S \cdot G_d \cdot G_{l\text{-}o}}{2\pi R_T} \qquad \text{G.4}$$

where $G_{l\text{-}o}$ is the gear ratio between the layshaft and the transmission output shaft, selected by the driver. Finally, the rotational speed of the transmission input shaft, which is equal to the engine speed (N_e) except when the clutch is slipping, can be calculated from:

$$N_e = N_{layshaft} \cdot G_{i\text{-}l} = \frac{S \cdot G_d \cdot [G_{l\text{-}o} \cdot G_{i\text{-}l}]}{2\pi R_T} = \frac{S \cdot G_d \cdot [G_t]}{2\pi R_T} \qquad \text{G.5}$$

where $G_{i\text{-}l}$ is the gear ratio between the transmission input shaft and the layshaft. The term in square brackets in Equation G.5 is the "overall" transmission gear ratio for the gear selected by the driver. Thus, given the vehicle speed, the rolling radius of the driven tires, the differential gear ratio, and the transmission gear ratio, calculating the engine speed is straightforward, requiring knowledge of only the vehicle speed, the rolling radius of the tires, the differential gear ratio, and the transmission gear ratio.

The fuel economy model user is required to input all of the gear ratios, except reverse. As discussed above, each of the gear ratios is the net effect of two gear pairs. As discussed below, calculation of the efficiency of the transmission requires knowledge of the gear ratios for both of these gear pairs, $G_{i\text{-}l}$ and $G_{l\text{-}o}$, but the fuel economy model user has only supplied the overall gear ratios. Fortunately, Kluger and Long (1999) have found that $G_{i\text{-}l}$ is typically 1.35 for a light-duty manual transmission. Obviously, the program calculates the unknown gear ratio between the layshaft and the transmission output shaft via:

$$G_{l\text{-}o} = \frac{G_t}{G_{i\text{-}l}} = \frac{G_t}{1.35} \qquad \text{G.6}$$

The “load” on the engine must also be known in order to calculate the fuel economy. The load is the torque required from the engine. The transmission and differential provide a torque multiplication and an rpm reduction simultaneously. However, the torque multiplication is inefficient and this must be accounted for in order to accurately calculate the torque required from the engine. The torque supplied at the tire-road interface is:

$$\tau_{road} = F_{mot} \cdot R_T \qquad \text{G.7}$$

The motive force equals the resistive force when moving at steady vehicle speed. When the motive force exceeds the resistive force, the vehicle is accelerating, and the vehicle decelerates when the motive force is less than the resistive force. Equations G.8 and 5.25 may be combined to yield:

$$\tau_{road} = \left(m_e \frac{dS}{dt} + A + B \times S + C \times S^2 \right) \cdot R_T \qquad \text{G.8}$$

where m_e is the effective mass of the vehicle and A-B and Care the road load coefficients for the specific vehicle being modeled.

Due to the inefficient torque multiplication by the differential, the torque supplied to the driveshaft by the transmission output shaft was provided by Equation G.3. After substitution of Equation G.3 into Equation G.8, this relationship becomes:

$$\tau_{trans\ output} = \frac{\tau_{road}}{G_d \eta_d} = \frac{\left(m_e \frac{dS}{dt} + A + B \times S + C \times S^2 \right) \times R_T}{G_d \eta_d} \qquad \text{G.9}$$

where the efficiency of the differential is obtained via Equation G.1. Finally, the torque supplied by the engine (τ_e) to the transmission input shaft, accounting for the inefficient torque multiplication by the transmission, is:

$$\tau_e = \frac{\tau_{trans\ output}}{G_t \eta_t} = \frac{\left(m_e \frac{dS}{dt} + A + B \times S + C \times S^2 \right) \cdot R_T}{G_t \eta_t G_d \eta_d} \qquad \text{G.10}$$

Therefore, in order to back-calculate the instantaneous engine load (τ_e), the efficiency of the transmission must be simulated. As noted above, two gear pairs act in series to produce the overall gear ratio. That is, two gear pairs are always engaged, such that an overall “high” gear ratio of 1.0:1 that involves an input-to-layshaft gear ratio of 1.35:1 must necessarily involve a layshaft-to-output shaft gear ratio of 1/1.35 or 0.74:1 whereas an overall “low” gear ratio of 2.53 with an input-to-layshaft gear ratio of 1.35:1 must necessarily involve a layshaft-to-output shaft gear ratio of 2.53/1.35 or 1.87:1

The efficiency of a manual transmission is a result of energy losses in both of these gear pairs, but losses in the transmission due to bearings, seals, and “windage” (aerodynamic and hydrodynamic drag of the bearings and, especially, all of the rotating gears) must also be accounted for. This relationship may be expressed as:

$$\eta_{man\ trans} = \eta_{GP1} \cdot \eta_{GP2} - x_{other}$$

$$= \left(1 - \frac{\mu_f}{R_{b,D,i\text{-}l}}\left|1 - \frac{1}{G_{i\text{-}l}}\right|\frac{L^2_{D,i\text{-}l} + L^2_{d,i\text{-}l}}{\left|L_{D,i\text{-}l} - L_{d,i\text{-}l}\right|}\left[1 - \varepsilon_{i\text{-}l} + \varepsilon^2_{i\text{-}l}\right]\right) \cdot \left(1 - \frac{\mu_f}{R_{b,D,l\text{-}o}}\left|1 - \frac{1}{G_{l\text{-}o}}\right|\frac{L^2_{D,l\text{-}o} + L^2_{d,l\text{-}o}}{\left|L_{D,l\text{-}o} - L_{d,l\text{-}o}\right|}\left[1 - \varepsilon_{l\text{-}o} + \varepsilon^2_{l\text{-}o}\right]\right) - x_{other} \qquad \text{G.11}$$

where μ_f is the friction coefficient between the gear pair (for which the American Gear Manufacturers Association suggests 0.6), $G_{i\text{-}l}$ is the gear ratio between the input shaft and the layshaft (as noted above, this is typically 1.35 according to Kluger and Long [1999]), $G_{l\text{-}o}$ is the gear ratio between the layshaft and the output shaft (calculated via Equation G.6 from the overall gear ratio for each specific transmission gear), $R_{b,D}$ is the radius of the drive gear base circle, subscripts i-l and l-o refer to the input shaft to the layshaft and the layshaft to the output shaft, respectively, ε is the contact ratio between the gear pairs (for which the minimum value of 1.2 was used for the initial version of the vehicle-specific fuel economy model), L_D and L_d are characteristic lengths of the drive and driven gears, respectively, and x_{other} is the fractional energy loss due to "windage" (assumed to be 0.05—an additional 5% energy loss—in the initial version of the manual transmission efficiency model).

The base circle radius of each of the drive gears (needed for use in Equation G.11) was estimated from the pitch radius (R_p) of that gear from:

$$R_{b,D,i\text{-}l} = R_{p,D,i\text{-}l}\cos\alpha_n$$
$$R_{b,D,l\text{-}o} = R_{p,D,l\text{-}o}\cos\alpha_n \qquad \text{G.12}$$

where α_n is the normal pressure angle of the gears (a 20^o normal pressure angle is most widely used due to its versatility, so this is the angle that was assumed for this model). In turn, the pitch radius was calculated from:

$$R_{p,D,i\text{-}l} = \frac{C}{\left(1 + \frac{t_{d,i\text{-}l}}{t_{D,i\text{-}l}}\right)} = \frac{C}{\left(1 + G_{i\text{-}l}\right)}$$
$$R_{p,D,l\text{-}o} = \frac{C}{\left(1 + \frac{t_{d,l\text{-}o}}{t_{D,l\text{-}o}}\right)} = \frac{C}{\left(1 + G_{l\text{-}o}\right)} \qquad \text{G.13}$$

where C is the center-to-center distance between the input shaft and the layshaft (which is the same as the center-to-center distance between the layshaft and the output shaft, assumed to be 75 mm for the initial version of the light-duty transmission efficiency model), and t_d and t_D are the number of teeth on the driven and drive gears (usually referred to as the gear and the pinion), respectively, although the number of teeth is not directly needed for the model.

The pitch circle radii from Equation G.13 are also needed to calculate the characteristic lengths required for use in Equation G.11:

$$L_{D,i\text{-}l} = R_{p,D,i\text{-}l}\sin\alpha_n$$
$$L_{d,i\text{-}l} = R_{p,d,i\text{-}l}\sin\alpha_n$$
$$L_{D,l\text{-}o} = R_{p,D,l\text{-}o}\sin\alpha_n$$
$$L_{d,l\text{-}o} = R_{p,d,l\text{-}o}\sin\alpha_n \qquad \text{G.14}$$

That is, the initial version of the model for the efficiency of a light-duty manual transmission requires only the number of gears and the gear ratios as inputs, and relies on estimates of 1) the center-to-center distance between the input (or output) shaft and the layshaft, 2) the typical input-to-layshaft gear ratio, 3) an estimate of the gear pair contact ratio, and 4) an estimate of the relatively small energy losses due to windage, bearings, and seals.

This model for the efficiency of a manual transmission suffers from lack of any dependence of the efficiency upon engine speed, engine torque, or oil temperature. As shown by van Dongen (1982), the rpm dependence is relatively weak, as is the torque dependence until the torque input is relatively low (the efficiency decreases rapidly as the torque inputs falls below ~25% of maximum torque). Also, the dependence on oil temperature is linear and relatively weak (van Dongen, 1982). The torque, rpm, and oil temperature effects on the efficiency of manual transmissions will be accounted for during the extension of TxDOT Project 0-5974.

For the initial version of the model for the efficiency of the transmission, it was assumed that:

$$\eta_t = \eta_{man\ trans} - \frac{Z}{100} \quad \text{G.15}$$

where, it was assumed that:

$$Z = \begin{cases} 0\% & : \text{ manual transmission} \\ 10\% & : \text{ automatic transmission} \\ 5\% & : \text{ automatic transmission with lockup torque converter} \\ 0\% & : \text{ semi-automatic (automated automatic)} \end{cases} \quad \text{G.16}$$

That is, for automatic transmissions, the efficiency of a manual transmission that has the same number of gears and the same gear ratios is first calculated, then the additional losses for an automatic transmission are accounted for using Equations G.15 and G.16. More accurate models for a manual transmission and for the various types of automatic transmissions will be developed during the extension of TxDOT Project 0-5974.

A gear shift strategy must also be simulated. A very simple gear shift strategy that depends only upon vehicle speed was used for the vehicle-specific fuel economy model up to the end of FY 2009. A more sophisticated gear shift model will be developed during the research extension of TxDOT Project 0-5974.

G.3. Engine Model for Light-Duty Vehicles

Virtually all light-duty vehicles in the U.S. use homogeneous charge gasoline engines. For the purpose of predicting the efficiency of homogeneous charge gasoline engines, it is most convenient to divide the overall engine efficiency into its component parts:

$$\eta_e = \eta_c \eta_m \eta_{it} \quad \text{G.17}$$

where η_c is the combustion efficiency (the efficiency of converting the chemical energy of the fuel to thermal energy), η_m is the mechanical efficiency (the efficiency of overcoming frictional, parasitic, and viscometric losses between the top of the pistons and the engine output shaft), and η_{it} is the indicated thermal efficiency (the efficiency of converting thermal energy to useful work at the top of the piston).

Models for each of these efficiencies are discussed below.

G.3.1. Combustion Efficiency Model for Light-Duty Vehicles

For the initial vehicle-specific, driving style dependent fuel economy model, a very simple model for the efficiency of the combustion process in homogeneous charge gasoline engines was used (Matthews, 2009):

$$\eta_c = \begin{cases} 1.0 \text{ if } \phi \le 1.0 \\ \dfrac{1}{\phi} \text{ if } \phi \ge 1.0 \end{cases} \qquad \text{G.18}$$

where η_c is the dimensionless combustion efficiency and ϕ is the equivalence ratio. The equivalence ratio is the ratio of the actual fuel/air ratio to the stoichiometric fuel/air ratio, so that for all fuels $\phi >1$ is fuel-rich and $\phi <1.0$ is fuel-lean operation.

A more sophisticated combustion efficiency model will be used during the next phase of TxDOT Project 0-5974.

G.3.2. Mechanical Efficiency Model for Light-Duty Vehicles

For the initial estimate of vehicle-specific, driving style dependent fuel economy, a simplified model for the efficiency of overcoming the frictional and parasitic losses of the engine was used. Specifically, the mechanical efficiency of light-duty gasoline engines is of the order of 85% at moderate and high load, but decreases to 0% at no load. It was assumed that the mechanical efficiency is constant for loads greater than or equal to 25% but decreases linearly to 0 when the fractional load (*L*) on the engine is 0:

$$\eta_m = \begin{cases} 0.85 \text{ if } L \ge 0.25 \\ \dfrac{0.85}{0.25} \times L \text{ if load} \le 0.25 \end{cases} \qquad \text{G.19}$$

In order to use Equation G.19 to calculate the mechanical efficiency, the instantaneous fractional load on the engine must be back-calculated.

$$L = \left. \frac{bp_{req}}{bp_{full\ load}} \right|_{same\ N} \qquad \text{G.20}$$

where bp_{req} is the instantaneous brake power required from the engine in order for the vehicle to travel at speed S and the denominator in Equation G.20 is the full load (wide open throttle for a spark ignition engine) brake power output of the engine at the same rpm at which the required brake power is being produced.

The brake power required from the engine is related to the instantaneous torque required (τ_e, calculated using Equation G.10) and the instantaneous engine speed (N_e, calculated using Equation G.5) via:

$$bp_{req} = 2\pi\tau_e N_e \qquad \text{G.21}$$

The final parameter required for evaluating the right hand side of Equation G.20 is the full load brake power output from the engine at rotational speed N_e (N_e =N below). Here, it is recognized that full load brake power is almost, but not quite, a linear function of engine speed, as illustrated in Figure G.1. The maximum power shown in Figure G.1 is the "rated" brake power at maximum engine rpm, and these two parameters are generally available to the users of this model. It was assumed that the relationship between full load brake power and engine rpm is precisely linear In order to determine the equation that describes this linear relationship, it was assumed that the full load power output from the engine at idle rpm (another user input) is 40% of the rated brake power. The resulting linear relationship:

$$
\begin{aligned}
bp_{WOT}(N) &= bp_{WOT}^{rated\ rpm} - \frac{bp_{WOT}^{rated\ rpm} - 0.4 \cdot bp_{WOT}^{rated\ rpm} \dfrac{N_{idle}}{N_{rated}}}{N_{rated} - N_{idle}} \left(N_{rated} - N\right) \\
&= bp_{WOT}^{rated\ rpm} \left[1 - \left(1 - 0.4 \frac{N_{idle}}{N_{rated}} \right) \left\{ \frac{N_{rated} - N}{N_{rated} - N_{idle}} \right\} \right]
\end{aligned}
\qquad \text{G.22}
$$

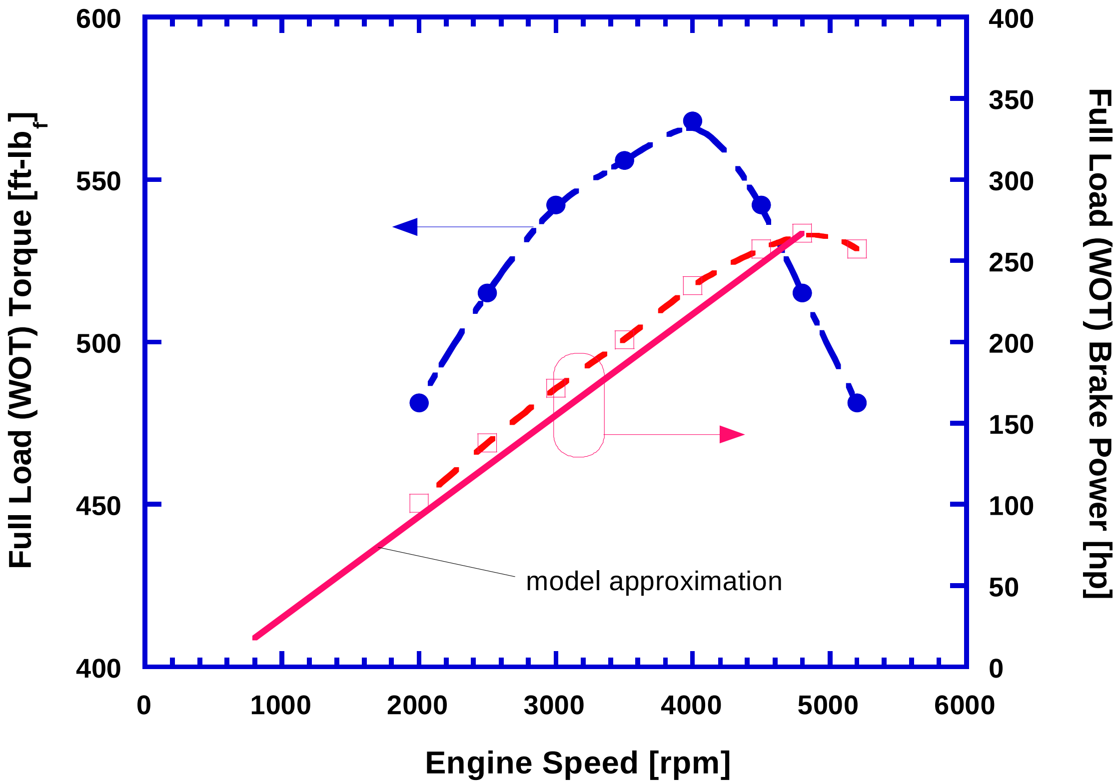


Figure G.1: Example of a Full Load Brake Power Curve

Figure G.1 is an illustration that the full load brake power output of a spark ignition engine varies approximately linearly with engine speed (experimental data from www.geocities.com/MotorCity/7610/dyno.htm for a 5.7 L V8). Additionally, Figure G.1 shows that the assumption used to generate our model for the full load power curve yields reasonably good agreement with the experimental data, at least for this engine. Therefore, the full load power at any engine speed was estimated using Equation G.22.

The user will be asked to input the engine displacement, the advertised power of the engine (this is the “rated” power), the engine rpm that corresponds to this power, and the idle rpm. A MATLAB code then-calculates the brake power for full load (for spark ignition engines, this is wide open throttle or WOT) operation at this engine speed from Equation G.22, and the fractional load using Equation G.20.

An improved model for the mechanical efficiency of light-duty engines will be developed during the extension of TxDOT Project 0-5574.

G.3.3. Indicated Thermal Efficiency Model for Light-Duty Vehicles

The vast majority of engines used in light-duty vehicles are 4-stroke homogeneous charge spark ignition (SI) engines. This is the most commonly used engine in the world, and in fact this engine dominates the market by a significant margin. Therefore, for the initial version of our vehicle-specific, driving style dependent fuel economy model for light-duty vehicles, our research team focused on development of a simple model for the indicated thermal efficiency of such engines.

One method for predicting the indicated thermal efficiency of the homogeneous charge SI engine is to use the well known Air Standard Otto Cycle:

$$\eta_{ti} = 1 - \frac{}{r_c^{k-1}} \qquad \text{G.23}$$

where r_c is the compression ratio and k is the ratio of the specific heats of the air. This model treats the combustion process as a heat addition process at constant volume, neglects heat losses, assumes that air has constant specific heats, and neglects "pumping work," which quantifies the efficiency penalty that occurs at part throttle due to pulling the fresh charge into the combustion chamber during the intake stroke and pushing the exhaust products out of the combustion chamber during the exhaust stroke. Due to these assumptions (and others not listed), Equation G.23 overestimates the indicated thermal efficiency by at least a factor of two.

A better simulation for the indicated thermal efficiency of 4-stroke homogeneous charge SI engines can be obtained via the Air Equivalent SI (AESI) engine model. The AESI model accounts for specific heats that are functions of temperature, accounts for pumping work, and indirectly accounts for the composition of the working fluid. The AESI engine model is discussed in detail by Matthews (2009) and, therefore, a detailed discussion of the modeling equations and solution procedure is not presented here. A MATLAB version of the AESI simulation was generated for TxDOT Project 0-5974 and embedded in the vehicle-specific fuel economy model.

However, because the AESI model accounts for part load operation, a necessary input to this model is a specification of either the instantaneous percent load on the engine or the instantaneous Manifold Absolute Pressure (MAP, in the intake manifold). Of these two measures of the load, the instantaneous percent load is more useful for the present modeling purposes. The technique used to calculate the instantaneous fractional load, L, was previously discussed with respect to Equations G.20, G.21, and G.22. This aspect of the technique for predicting the fuel economy of a light-duty vehicle is also of interest because the improved model for the indicated thermal efficiency to be developed during the FY 2010 and FY 2011 extensions of TxDOT Project 0-5974 will also require the specification of the load imposed on the engine.

Therefore, the instantaneous fractional load on the engine, *L*, needed for use both in Equation G.19 and as input to the model for the indicated thermal efficiency of the engine, is easily calculated.

Equations G.20 and G.21 and the AESI engine model all also need the instantaneous engine speed. This is easily calculated from Equation G.5 given the instantaneous vehicle speed, the instantaneous transmission gear ratio, the differential gear ratio, and the rolling radius of the driven tires.

The AESI technique relies on several assumptions that yield a prediction that is too high. An improved and very accurate model for the indicated thermal efficiency of light-duty spark ignition engines will be generated during the next phase of TxDOT Project 0-5974.

G.4. Model for the Torque Multiplication and Efficiency of a Heavy-Duty Differential and Transmission

For the initial version of a fuel economy model for heavy-duty vehicles, the models for the performance (torque multiplication, rotational speed reduction, and efficiency) of the transmission and the differential are identical to those for light-duty vehicles, except that the user can input up to ten transmission gear ratios instead of the maximum of six for light-duty vehicles. Also, a 10-speed transmission accomplishes this via a 5-speed gear box followed by a 2-speed gear box. In this case, the efficiency of all four gear pairs must be accounted for:

$$\eta_{man\ trans} = \eta_{GP1} \cdot \eta_{GP2} \cdot \eta_{GP3} \cdot \eta_{GP4} - x_{other} \qquad \text{G.24}$$

where the gear pair efficiencies are calculated using the procedure discussed with respect to light-duty transmissions.

G.5. Engine Model for Heavy-Duty Vehicles

Virtually all heavy-duty vehicles in the U.S. use diesel engines. We used a commercial software package to model the heavy-duty engine: AVL's Cruise code. This package can be used to simulate anything from a race car to a heavy-duty vehicle. Our research team was primarily interested in using this software to extract the overall engine efficiency of a heavy-duty diesel engine as a function of both engine speed and engine load.

AVL Cruise is reasonably accurate for heavy-duty diesel engines prior to the implementation of EPA's 2007 heavy-duty diesel emissions standards. The user can specify the vehicle, with the user providing coastdown coefficients, the differential gear ratio and efficiency, the transmission gear ratio and efficiency, the vehicle speed, and the grade. Our goal was to run enough simulations under enough operating conditions so that we could extract a "look-up" table of the brake specific fuel consumption (bsfc) as a function of engine speed and load. The bsfc is defined in Equation 5.3, where it is also related to the overall engine efficiency and the Lower Heating Value (energy density) of the fuel. That is, given the bsfc and the Lower Heating Value of the fuel, the overall engine efficiency can be easily calculated.

This bsfc look-up table uses the brake mean effective pressure (bmep) as the load parameter rather than the torque, to allow this table to be as generic (applicable to diesel with various displacements) as possible. The bmep is a normalized torque that is routinely used to compare engines and/or to specify engine load:

$$\text{bmep} \equiv \frac{\text{bp} \cdot x}{D \cdot N} \qquad \text{G.25}$$

where x is the number of revolutions per power stroke (2 for a 4-stroke engine, as used in heavy-duty vehicles) and D is the engine's displacement.

The look-up table we generated is provided as Table G.1.

Table G.1: Look-Up Table for the Brake Specific Fuel Consumption (in g/kW-hr) of Heavy-Duty Diesel Engines Prior to MY 2007

	Engine Speed [rpm]						
BMEP [bar]	800	1000	1200	1400	1600	1800	2000
19.8	272	227	196	188	183	191	200
18.6	272	227	196	188	183	191	200
16.3	272	227	198	189	187	192	201
14.0	276	228	200	191	190	194	202
11.6	280	231	202	194	192	195	204
9.3	280	235	203	199	196	197	206
7.0	288	242	209	205	203	203	212
4.7	302	254	220	220	219	219	227
2.3	344	280	242	253	257	265	265

Appendix H: Coastdown Test Protocol

A requirement of TxDOT Project 0-5974, “Estimating Texas Motor Vehicle Operating Costs,” was to develop a model that can be used to predict the fuel economy for any vehicle whether it is a light-duty vehicle or a heavy-duty vehicle. EPA’s website provides data that can be used for this purpose for all light-duty vehicles that are sold in the U.S. However, the required data are not available for heavy-duty vehicles.

Therefore, we had to generate “coastdown” data for all heavy-duty vehicles of interest for this project. Section H.1. summarizes the SAE recommended practice for coastdown tests. Specific requirements for instrumentation are summarized in Section H.2. An example vehicle data sheet from one of the coastdown tests is provided in Section H.3.

H.1. SAE Coastdown Test Requirements

The protocol specified in SAE Recommended Practice J1263, "Road Load Measurement Using Coastdown Techniques," is summarized in the following section.

H.1.1. Prior to Each Coastdown Test

1) A log form, supplied by the research team, must be filled out for each vehicle (an example is provided in Section H.3).

2) The vehicle must be driven a minimum of 30 minutes at an average speed of 50 mph immediately prior to the test.

3) The tire pressure in all of the tires must be measured to an accuracy of ±0.5 psig.

4) The test vehicle should have accumulated a minimum of 300 miles prior to testing. The tires should have accumulated a minimum of 100 miles and should have at least 75% of the original tread depth remaining.

H.1.2. During Each Coastdown Test

1) The ambient temperature and pressure must be measured during each coastdown run. The temperature indicating device(s) must have a resolution of 2 ^{o}F and an accuracy of ±2 ^{o}F and the sensing element must be shielded from radiant heat sources. For the measurement of ambient pressure, a barometer with an accuracy of ±0.7 kPa (±0.2 in of Hg) is required.

2) The wind speed and direction must be continuously monitored during the tests. Wind measurements should permit the determination of the average longitudinal and crosswind components within ±1 mph.

3) Coastdown tests must be performed going in both directions, for a total of at least 5 “paired” tests for each vehicle and configuration (payload weight, tire type, etc.). A test pair consists of the data from a coastdown in each direction.

4) The vehicle windows must be closed during the tests. At the start of each run, the vehicle must accelerate to 65 mph at which time the recording equipment is started, and the

transmission is then shifted into neutral so that the engine idles during the coastdown. The vehicle clutch must be engaged (clutch pedal out all the way) during the coastdown. When the vehicle stops, the recording equipment is stopped, the transmission is engaged, and preparations for the next run are performed.

5) While coasting, lane changes should be avoided if at all possible. If necessary, they should be done as slowly as possible and over a distance of at least a quarter mile. If such a gradual change cannot be made, the coastdown run must be aborted.

6) During each coastdown run, the vehicle speed must be measured as a function of time using an on-board data acquisition system.

H.1.3. After the Coastdown Tests

1) Each vehicle must be weighed (alternatively, this can be done prior to the coastdown tests). The weighing instrument must be calibrated first and it must be accurate to within ±10 lb_f per axle.

2) The weight of each "wheel assembly" (the wheel, tire, and everything that rotates with them, except that axles can be ignored due to their small radius relative to the other rotating components) must be measured (alternatively, this can be done prior to the coastdown tests).

3) The frontal area of each test vehicle must be accurately determined.

H.1.4. Limitations on Testing

1) The ambient temperature must be between 30 ^{o}F and 90 ^{o}F and preferably between 41 ^{o}F and 90 ^{o}F. Data obtained at temperatures outside this range cannot be reliably adjusted to standard conditions.

2) Tests may not be conducted when wind speeds average more than 10 mph or when peak wind speeds are more than 12.3 mph. The average of the component of the wind velocity <u>perpendicular</u> to the test road may not exceed 5 mph.

3) Roads must be dry, clean, smooth, and must not exceed 0.5% grade (because the grade on SH 45 South exceeds this, we will need to correct our results for the effects of grade). In addition, the grade should be constant and the road should be straight because variations in grade or straightness can significantly affect results. The road surface should be concrete or rolled asphalt (or equivalent) in good condition because rough roads can significantly affect rolling resistance. In addition, tests may not be run during foggy or rainy conditions: roads must be dry.

H.2. Detailed Specifications for the Required Instrumentation

1. <u>On-board data logger</u> to measure vehicle speed as a function of time.
    Time:
      (1) Required accuracy: ±0.1 % of total coastdown time interval
      (2) Required resolution: 0.1 s
    Speed:

(1) Required accuracy: ±0.25 mph
(2) Required resolution: 0.1 mph

2. Ambient temperature sensing device (sensing element must be shielded from radiating effects like direct sunlight)
   (1) Required accuracy: ±2 ^{o}F
   (2) Required resolution: 2 ^{o}F
3. Barometric pressure sensing device
   (1) Required accuracy: ±0.7 kPa (±0.2 in-Hg)
   (2) Required resolution: 0.1 kPa (0.03 in-Hg)
4. Anemometer or equivalent to measure wind speed and direction
   (1) Required accuracy: ±1.0 mph
   (2) Required resolution: 0.1 mph
5. Vehicle weight
   (1) Required accuracy: ±10 lb_f/axle
   (2) Required resolution: 1.0 lb_f
6. Tire pressure gauge
   (1) Required accuracy: ±0.5 psi
   (2) Required resolution: 0.1 psi

H.3. Example Coastdown Vehicle Data Sheet

A data sheet for one of the vehicles used for the coastdown tests for TxDOT Project 0-5974 is provided below as an example.

DATE: 3/8/2009

TEST DRIVER: WAYNE HEIKKILA
TEST ENGINEER: MURAT ATES

VEHICLE DESCRIPTION: **MUST BE FILLED IN ON DAY OF COASTDOWN TESTS**

MODEL YEAR:	10/07	VIN NUMBER:	1FTPX12V98FA48730	ENGINE YEAR:	2007 (TRITON)
MAKE:	FORD	LICENCE PLATE:	102-6208	ODOMETER:	15181.2 miles
MODEL:	F150 XL (5.4L)	CLASS:	Standard Size Pick-up	TXDOT #	29-5962-J

TIRES* : **MUST BE FILLED IN BEFORE COASTDOWN TESTS AT THE PREPARATION AREA**

SELECT UNITS
psi [X]
kPa [ ]

TIRE TYPE: M+S
TIRE SIZE: P235/70R 17
TIRE MAKE: HANKOOK DYNAPRO AS

PREPARATION AREA TEMPERATURE: 81.6 [X] [ ]
46% Humidity Ratio

	Manufacturer Specified Tire Pressure	Actual Tire Pressure	TREAD DEPTH > 75%	
Right Front:	38	38	YES [X]	NO [ ]
Right Axle 2 Inside:			YES [ ]	NO [ ]
Right Axle 2 Outside:	38	38	YES [X]	NO [ ]
Right Axle 3 Inside:			YES [ ]	NO [ ]
Right Axle 3 Outside:			YES [ ]	NO [ ]
Right Axle 4 Inside:			YES [ ]	NO [ ]
Right Axle 4 Outside:			YES [ ]	NO [ ]
Right Axle 5 Inside:			YES [ ]	NO [ ]
Right Axle 5 Outside:			YES [ ]	NO [ ]

*** THE TIRES SHOULD HAVE ACCUMULATED A MINIMUM OF 100 MILES AND** **OK**
SHOULD HAVE AT LEAST 75% OF THE ORIGINAL TREAD DEPTH REMAINING, OTHERWISE TEST CANNOT BE STARTED **OK**

TIRES* : **MUST BE FILLED IN BEFORE COASTDOWN TESTS AT THE PREPARATION AREA**

SELECT UNITS
psi [X]
kPa [ ]

	Manufacturer Specified Tire Pressure	Actual Tire Pressure	TREAD DEPTH > 75%	
Left Front:	38	38	YES [X]	NO [ ]
Left Axle 2 Inside:			YES [ ]	NO [ ]
Left Axle 2 Outside:	38	38	YES [X]	NO [ ]
Left Axle 3 Inside:			YES [ ]	NO [ ]
Left Axle 3 Outside:			YES [ ]	NO [ ]
Left Axle 4 Inside:			YES [ ]	NO [ ]
Left Axle 4 Outside:			YES [ ]	NO [ ]
Left Axle 5 Inside:			YES [ ]	NO [ ]
Left Axle 5 Outside:			YES [ ]	NO [ ]

*** THE TIRES SHOULD HAVE ACCUMULATED A MINIMUM OF 100 MILES AND** **OK**
SHOULD HAVE AT LEAST 75% OF THE ORIGINAL TREAD DEPTH REMAINING, OTHERWISE TEST CANNOT BE STARTED **OK**

FINAL CHECK: **MUST BE FILLED IN BEFORE STARTING COASTDOWN TESTS AT THE FIELD**

VEHICLE WINDOWS CLOSED* :	YES [X]	NO [ ]
FOG* :	YES [ ]	NO [X]
ROAD IS DRY* :	YES [X]	NO [ ]

*** ANSWERS SHOULD BE [YES, NO, YES] RESPECTIVELY, OTHERWISE TEST CANNOT BE STARTED**

THE TEST VEHICLE SHOULD HAVE ACCUMULATED A MINIMUM OF 300 MILES PRIOR TO TESTING. **OK**
VEHICLE MUST BE DRIVEN A MINIMUM OF 30 MINUTES AT AN AVERAGE OF 50 MPH IMMEDIATELY PRIOR TO TEST. **OK**

OTHERWISE TEST CANNOT BE STARTED

AMBIENT TEMPERATURE* & HUMIDITY :

MUST BE FILLED IN DURING COASTDOWN TESTS

SELECT UNITS

[X]

[ ]

MINIMUM TEMPERATURE:	75.3		MAXIMUM TEMPERATURE:	82.7
AVERAGE TEMPERATURE:	79	= (MIN+MAX) / 2		
MINIMUM HUMIDITY:	55.0%		MAXIMUM HUMIDITY:	70%
AVERAGE HUMIDITY:	62.5%	= (MIN+MAX) / 2		

*** AMBIENT TEMPERATURE SHOULD BE BETWEEN 41 - 90 , OTHERWISE THE TEST IS VOID** **OK**

ATMOSPHERIC PRESSURE:

MUST BE FILLED IN DURING COASTDOWN TESTS

SELECT UNITS

in.Hg [X]

kPa [ ]

START PRESSURE:	29.26		FINAL PRESSURE:	29.334
AVERAGE PRESSURE:	29.297	=(START+FINAL) / 2		

WIND SPEED:

MUST BE FILLED IN DURING COASTDOWN TESTS

SELECT UNITS

mph [X]

km/h [ ]

AVERAGE WIND SPEED:	6.8	< 10 mph (16 km/h)*	DIRECTION:	90.6 deg
PEAK GUSTS:	14.1	< 12.2 mph (20 km/h)*		
AVERAGE CROSSWIND COMPONENT:	6.8	< 5 mph (8 km/h)*		

*** IF THESE VALUES ARE EXCEEDED, THE TEST IS VOID**

WHEELS:

THIS BOX CAN BE FILLED IN BEFORE OR AFTER THE COASTDOWN TESTS

SIZE: 17 WHEEL COVERS: YES [X] NO [ ]

ENGINE & DRIVETRAIN SPECIFICATIONS:

THIS BOX CAN BE FILLED IN BEFORE OR AFTER THE COASTDOWN TESTS

DISPLACEMENT:	5.4 L (330 cu. In.)	COMPRESSION RATIO:	9.8 : 1
BORE:	3.55 in.	MAX POWER:	300 hp @ 5000 rpm
STROKE:	4.16 in.	MAX TORQUE:	365 lb-ft @ 3750 rpm
# OF CYLINDERS:	8		

GEAR RATIOS: *	2.84 / 1.55 / 1.00 / 0.70
AXLE RATIOS: *	4.10 : 1
TRANSFER CASE RATIO:	1.00
VEHICLE WEIGHT:	5890 lb
OVERDRIVE RATIO:	1.00

*** STARTING FROM SMALLEST GEAR AND FIRST AXLE**

WEIGHT:

THIS BOX CAN BE FILLED IN BEFORE OR AFTER THE COASTDOWN TESTS

SELECT UNITS

lbs [X]

kg [ ]

VEHICLE TEST WEIGHT (DRIVER & INSTRUMENTATION): 5890

TIRE/WHEEL/BRAKE ASSEMBLY: *

Right Front Assembly:	96	Left Front Assembly:	96
Right Axle 2 Assembly:		Left Axle 2 Assembly:	
Right Axle 3 Assembly:		Left Axle 3 Assembly:	
Right Axle 4 Assembly:		Left Axle 4 Assembly:	
Right Axle 5 Assembly:		Left Axle 5 Assembly:	
Right Rear Assembly:	88	Left Rear Assembly:	88

*** WEIGHT OF ALL ROTATING COMPONENTS EXCEPT AXLES**

MISCELLANEOUS:

THIS BOX CAN BE FILLED IN BEFORE OR AFTER THE COASTDOWN TESTS

CHECK VEHICLE SUSPENSION HEIGHTS IF THEY COMPLY WITH THE MANUFACTURER SPECIFICATIONS [X]
CHECK ENGINE FLUID LEVELS [X]
TAKE FRONTAL AREA PICTURE [X]