EFFECT OF PAVEMENT TYPE ON FUEL CONSUMPTION IN CITY DRIVING

by

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DEDICATION

To my parents.

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ABSTRACT

EFFECT OF PAVEMENT TYPE ON FUEL CONSUMPTION IN CITY DRIVING

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Vehicular fuel consumption and emissions are two increasingly important measures of effectiveness of sustainable transportation systems, particularly considering that mobile sources in the U.S. account for the largest consumption of energy and generation of air pollution. Improving the energy efficiency of the transportation sector including improving vehicle shape, weight, engine size, and tire quality could play a vital role in reducing fuel consumption and exhaust gas emissions. Pavement surface type and other surface characteristics such as skid resistance and roughness affect vehicular fuel consumption.

The main objective of this study has been to investigate any differences that might exist in fuel consumption when operating an instrumented van on an Asphalt Concrete (AC) versus on a Portland Cement Concrete (PCC) pavement under city driving conditions. The overall study goal has been to recommend consideration of such user costs or savings in the life cycle analysis of alternative pavement designs for city streets.

Fuel consumption measurements were made on multiple runs under two driving modes: 30-mph constant speed and 3-mph/sec acceleration for 10 seconds. All factors that could affect fuel consumption, other than the pavement surface were either controlled or kept the same during the measurement runs. Those factors included speed, ambient temperature, relative humidity, wind speed and direction, vehicle weight, tire pressure, and use of auxiliary devices in the vehicle.

The results indicated that the differences in fuel consumption rates were statistically significant at a 10% level of significance under both constant speed and acceleration modes, with the fuel consumption rates on the PCC pavements being lower. The extrapolated results also indicated that if all the annual vehicle miles of travel in the Dallas-Fort Worth region took place at a constant speed of 30 mph on PCC pavements, the statistically lower fuel rates could result in an annual savings of about 401 million gallons of fuel and an annual CO_2 reduction of about 3.53 million metric tons. Using an average gasoline price of about \$3.29 per gallon and an average CO_2 clean-up cost of about \$18 per metric ton, these differences would amount to a savings of about \$1.38 billion per annum in the DFW region. The potential savings or costs in fuel consumed and the CO_2 emissions generated can be substantial over the design life of a road project. It is therefore recommended that these savings or costs be considered in the life cycle cost analysis of alternative road construction projects.

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CHAPTER 1

INTRODUCTION

1.1 Problem Definition

Vehicular fuel consumption and emissions are two increasingly important measures of effectiveness of sustainable transportation systems, particularly considering that mobile sources in the U.S. account for the largest consumption of energy and generation of air pollution. According to the U.S. Bureau of Transportation Statistics(U.S. Bureau of Transportation Statistics, 2011), there were 255,917,664 registered vehicles in the U.S. in 2008. Gasoline, which is the main product from crude oil refining, is one of the major fuels consumed by vehicles in the U.S. with a consumption level of over 70 billion gallons in 2007. This is about half of the total gasoline consumption for any purpose in the U.S. (TRB Special Report 285, 2006). As such, the transportation sector is also the largest emitter of CO_2 among all energy-use sectors such as industrial, residential, and commercial sectors. Among three common fossil fuels – petroleum, natural gas, and coal – 96% of the 2007 U.S. primary transportation energy consumption relied on petroleum or crude oil (U.S. Department of Energy, 2008). This trend continues despite the oil price increases which peaked at over $140 a barrel in June 2008.

In motor vehicles, CO_2 is the by-product of the combustion process and is released to the atmosphere as a tailpipe emission. It is one of the greenhouse gases contributing to global warming. Between 1990 and 2007, the CO_2 emissions of the transportation sector grew the most, a 26.8% increase over the 10-year period (1990 – 2000) and a 1.4% increase from 2006 to 2007 alone (U.S. Department of Energy, 2008). As a result, improving the energy efficiency of the transportation sector including improving vehicle shape, weight, engine size, and tire quality could play a vital role in reducing fuel consumption and exhaust gas emissions. Pavement surface type and surface characteristics such as skid resistance, roughness, and longitudinal slope also affect vehicular fuel consumption.

1.2 Study Objectives

This study aims at investigating vehicular fuel consumption differences under two different pavement surface types when operating a vehicle under urban driving speeds. It follows an experimental design which aims at accounting for most factors affecting fuel consumption in order to isolate the effect of pavement type on fuel consumption. The main objective is to compare fuel consumption of an instrumented test vehicle as a function of pavement surface material through direct field measurements. The study will focus on paved city streets since urban driving accounts for a substantial share of the total vehicular energy consumption and generated emissions. Two types of pavement surfaces, namely Portland Cement Concrete (PCC) and Asphalt Concrete (AC), are studied. Using known scaling factors documented in energy consumption literature relating vehicle weight to fuel consumption, the study results for the test vehicle are extrapolated to other vehicle types in the mix. This allows, as a second study objective, to establish a procedure in a spreadsheet format for estimating the total fuel savings for different pavement type scenarios. The latter would require, as an additional input variable, data on vehicle mix and vehicle miles traveled within a city or region of interest. Such data are published annually by the U.S. Bureau of Transportation Statistics (BTS). The procedure developed will provide the necessary tool to achieve a third objective, namely inclusion of potential fuel savings in the life-cycle cost analysis (LCCA) of alternative pavement designs.

Based on the above objectives, the main outcomes of the study are anticipated to be:

a. A statistical comparison of relative fuel economy differences for concrete and asphalt pavement surfaces under urban driving conditions.

b. The development of a spreadsheet tool to estimate fuel consumption for various pavement surfaces.

c. The development of a procedure to include fuel consumption cost in the LCCA of different pavement design alternatives for a given pavement design or re-surfacing project.

1.3 Dissertation Overview

The dissertation is divided into five chapters. Chapter 1 is the introduction and problem definition. In chapter 2, the literature review discusses the background and impacts of fuel consumption and the use of LCCA for pavement design alternatives. Additionally, it reviews the factors that influence fuel consumption, followed by an overview of costs to include in LCCA.

Chapter 3 presents the research methodology employed in the study. It describes the criteria in selection of the test road sections and summarizes the characteristics of all test road sections. It also describes the features of the test vehicle, including the fuel meter equipment, temperature gauges, and an on-board data acquisition system. Additionally, this chapter describes how the data are collected as well as the data analysis approach. In chapter 4, the results are presented and discussed. Chapter 5 presents conclusions and recommendations.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In this chapter, studies related to this research are reviewed. The review is on the use of LCCA for pavement design alternatives, and the costs associated with LCCA. It also presents the findings related to factors affecting fuel consumption.

2.2 Background

The Transportation Research Board (TRB) Special Report 285 states that vehicular fuel consumption accounts for nearly half of the total energy consumption in the U.S. (TRB Special Report 285, 2006). About half of that amount is estimated to be due to urban city driving at speeds below 40 mph (Larson, 1992). As such, the oil crises of 1970s led to numerous research studies on vehicular fuel consumption. This led to advances in automotive design including lighter vehicles with more efficient engines, more energy efficient tires, to smoother roadway alignments, and to traffic engineering measures such as better timed traffic signals and national speed limit regulations.

The elemental fuel consumption model developed by scientists at the GM Research Lab (Evans et al., 1976a; Evans et al., 1976b) was the widely accepted model among the fuel consumption models developed in the 1970s. This model showed that the fuel consumption in a single vehicle varies greatly depending on many factors including speed, acceleration-deceleration cycle, vehicle weight, mechanical conditions of the vehicle (e.g. tire pressure, wheel alignment, and state of its carburetion system), ambient conditions such as wind and temperature, and pavement surface conditions. The model speculated that about 70% of the variability in a vehicle's fuel consumption is explained by speed alone. Also an important factor influencing the fuel consumption rate is the rolling pavement resistance, which is primarily a function of the pavement surface condition and type. The fuel consumption differences due to rolling resistance were expected to be particularly significant for trucks and other heavy vehicles.

Since the costs of road construction and maintenance constitute a large proportion of the highway infrastructure projects, the World Bank, which provides financial and technical assistance to developing countries, introduced the Highway Design and Maintenance (HDM) Standards Model (Archondo-Callao and Faiz, 1994). This program accounts for vehicle operating costs in addition to the construction, maintenance, and rehabilitation costs of alternative pavement designs. It also incorporates the LCCA as a basis for decision making in the selection of highway design alternatives.

The life-cycle cost in the HDM (Archondo-Callao and Faiz, 1994) included user costs in addition to conventional construction, maintenance and rehabilitation costs. The user costs were mainly the vehicle operating costs and exogenous costs such as the cost the society incurs as the result of road usage. The vehicle operating cost model contained variables related to vehicle characteristics such as engine size, speed, tire conditions, etc., and road characteristics such as smoothness and slope of the longitudinal profile. The smoothness and slope of the longitudinal profile were the only pavement characteristics used in the model for estimating the vehicle operating costs. The other pavement characteristics such as the pavement type became statistically less significant since data from both paved and unpaved roads were used. To enhance the Highway Design Model work, a New Zealand study by Walls and Smith (1998) further suggested that the smoothness of the longitudinal profile has little impact on the fuel consumption for paved roads in good condition.

Papagiannakis and Delwa (Papagiannakis, 1999b; Papagiannakis and Delwar, 1999a; Papagiannakis and Delwar, 2001a) developed a software program which highlighted the importance of incorporating vehicle operating costs in the life-cycle cost analysis of pavement projects. Their findings were later implemented in the Pavement Management System program of the Washington State Department of Transportation. They also paid special attention to the effect of roughness on the vehicle operating costs to illustrate the increase in these costs with the deterioration of the pavement.

In addition, many studies have attempted to systematically assess the effect of pavement surface material type on fuel consumption (Jonsson and Hultqvist, 2009; Taylor and Patten, 2006; Zaniewski, 1989; Zaniewski et al., 1982). Most of these studies focused on fuel consumption of vehicles on highways under fairly high operating speeds. A Canadian study (Taylor and Patten, 2006) performed measurement of fuel consumption using heavy trucks, while a Swedish study (Jonsson and Hultqvist, 2009) was conducted using passenger cars. Both study results indicated that there was potential fuel savings on PCC over AC pavements. Additionally, the research by Zaniewski (Zaniewski, 1989; Zaniewski et al., 1982), which was the earliest effort to investigate the effect of pavement type on fuel consumption, also pointed out that fuel consumption of a truck when travelling on PCC pavements is lower than when travelling on AC pavements. Because their study was focused on fuel consumption of trucks on highways and also due to other limitations of the methodology employed, this study has received substantial criticism (Bein and Biggs, 1993). Partly due to these issues, Zaniewski's findings have not been widely adopted by the pavement engineering community. Zaniewski's findings could also allow incorporating fuel economy improvements and emissions reductions in the life-cycle cost analysis of design alternatives for highway pavements. However, it is not readily clear whether and to what extent they are applicable to city streets, where the urban carbon footprint is becoming an increasingly important consideration in the analysis of design alternatives.

A synthesis study by the Ontario Hot Mix Producers Association, for example, cites that for every 1,000 kg of Portland cement, approximately 650 kg of carbon dioxide is produced while the carbon in the asphalt cement will never be released into the atmosphere (Brown, 2009). The Canadian study also compares two residential pavement cross-sections, a PCC and an asphalt pavement in southern Ontario. The study then proceeds to estimate the contributions of these two pavement materials to the carbon footprint of a one-kilometer long section and concludes that the HMA pavement generates only 22 percent of the carbon footprint of the PCC pavement, during pavement construction process. The computations are based solely on estimated CO_2 releases in the materials production as well as construction phase of the projects. While the study accounts for the CO_2 releases from cement kilns in estimating the carbon footprint of PCC projects, the portion of CO_2 releases from oil refineries attributable to asphalt production are not considered in making similar estimates for AC pavements. More importantly, this and other similar studies (VicRoads, 2008) do not consider the emissions resulting from the operation of motor vehicles over the design life of pavements in these calculations. A key conclusion of the current study is that over the design life of a pavement, the difference in the CO_2 amounts resulting from operation of motor vehicles on various pavement surfaces could be substantial and may in fact help dwarf any such differences estimated for the production and construction phases.

2.3 Factors Affecting Fuel Consumption

The effect on fuel consumption depends on a number of factors as follows:

2.3.1 Vehicle Weight

Vehicle weight is a significant factor in fuel consumption. The emissions and fuel consumption are greater for light trucks than those in the past. This indicates the increasing trend toward the larger and heavier light trucks, which in the past had less stringent emission standards and lower fuel efficiency (U.S. Environmental Protection Agency, 2000). However, automobile manufacturers currently must develop vehicles in accordance with the EPA emission standards as well as improving vehicle fleet gas mileage. Newer cars and trucks will use less gasoline and emit less pollution. Carbon dioxide, which is not classified as an emission, is the transportation sector's primary contribution to climate change. Its emissions are directly proportional to fuel consumption. A 1% decrease in fuel consumption results in a corresponding 1% decrease in carbon dioxide emissions (U.S. Environmental Protection Agency, 2000). A European study (Lubrizol, 2011) also shows that a 1% increase in fuel economy for one vehicle could lower CO_2 emissions by over 1.5 g/km.

Decreasing vehicle weight results in less energy required by the engine to accelerate the vehicle and less rolling resistance from vehicles' tires. A 1% weight reduction results in 0.42% fuel economy gain (Casadei and Broda, 2008). One study (An et al., 2002) also shows that when the car weight is decreased by 10%, the fuel economy would increase 3 to 8%. Removing excess weight from the vehicle helps reduce fuel consumption. It is shown that a reduction of 440 pounds (200 kg) can increase fuel efficiency by 5% in a midsize car (Pagerit et al., 2006).

2.3.2 Engine Oil

Engine oil is used as the lubricant in internal combustion engines. It performs many functions. The main function is to lubricate the moving components of the engine. It, thus, primarily reduces friction between moving components. Other functions are to clean, limit wear on the moving parts, inhibit corrosion, and cool the engine by carrying away the heat generated by the frictional losses.

When engine components move against each other, this causes friction which loses power by converting energy to heat. The contact between moving surfaces also wears those parts which could lead to lower engine efficiency. Hence, it diminishes power output and increases fuel consumption. The engine oil generates a separating film between surfaces of moving parts to minimize direct contact. About 67% of friction losses in the engine occur during this surface contact (Energy and Environmental Analysis Inc., 2001).

The property of the engine oil which reduces friction is its viscosity. Viscosity is a measure of oil's resistance to flow. As temperature decreases, oil viscosity increases. This accounts for increased fuel usage under low ambient temperatures and cold engine operations. In order for the engine to perform at its peak fuel efficiency, the oil viscosity must be high enough at high temperatures so that the oil film between moving parts does not break down, and low enough at low temperatures to protect the engine from cranking. Because friction loss between moving parts could affect from 10% to 40% of the energy input to the engine (Transportation Energy Management Program, 1982), nowadays, engine oil manufacturers develop their lubricant formulation to improve vehicles' fuel efficiency. Shell (2011) lubricant development program claims its engine oil yields 6.5% fuel efficiency improvement. However, the engine oil grade and viscosity to be used in a given vehicle is designated by the automobile manufacturers. The engine oil grade requirement can vary from country to country when climatic conditions are considered.

2.3.3 Tires

Tires also have an impact on fuel consumption because about 12 to 20% of the energy output is transmitted through the vehicle's driveline as mechanical energy to propel the wheels. Approximately 4 to 7% of the energy output is used by rolling resistance (TRB Special Report 286, 2006). When the vehicle moves, it encounters rolling resistance – the resistance that occurs when the vehicle tires rotate over the contact surface. It acts in the direction opposite to the direction of travel (see Figure 2.1). Basically, rolling resistance is the energy loss in rolling tires under the weight of the vehicle. The primary cause of loss of energy is the deformation and recovery of the tire, called hysteresis (Goodyear, 2008). The viscoelastic behavior of the rubber material of tire generates the energy loss. The rubber has an elastic property where all energy that is stored in the material during loading is returned when the load is removed, and the material rapidly recovers its shape. Nevertheless, for viscous behavior of rubber, the energy needed to deform the material is simultaneously transformed to heat. Consequently, as for any viscoelastic material, some of energy is recovered during load removal, while the remainder is transformed to heat (TRB Special Report 286, 2006).

Figure 2.1 Tire Rolling Resistance (Goodyear, 2008).

The TRB special report (2006) states that for most passenger vehicles, a 10% reduction in rolling resistance produces a 1 to 2% increase in fuel economy and a proportional reduction in fuel consumption. Additionally, in most passenger vehicles, Society of Automotive Engineers (SAE) paper (Sovran and Bohn, 1981) indicates that a 5 to 7% decline in rolling resistance will lead to a 1% benefit in fuel economy. However, tire rolling resistance measurement is usually performed as a laboratory test. The measurement procedures used with different instruments under different circumstances could generate variability of results.

Tire inflation pressure, tire diameter, tire tread, and tire construction have an effect on rolling resistance. Motorists should be aware that the proper inflation pressure is necessary for tire performance, safety and optimum fuel efficiency. Inflation pressure affects tire deformation. Lower pressure causes the tire sidewalls to flex more and generate higher rolling resistance. Keeping tires properly inflated is therefore important to prevent excessive deformation and hysteresis, and achieving best gas mileage. Studies indicate that for every 1 pound per square inch (psi) decline in tire pressure, fuel economy lowers by 0.3 to 1% (Transportation Energy Management Program, 1982; U.S. Department of Energy, 2010a). The figures are consistent to the U.S. EPA report (2006), mentioning Aerospace Corp. and Goodyear studies. It is found that fuel economy declines 1% for every 3.3 psi (Aerospace Corp) and 2.96 psi (Goodyear) decrease in tire pressure.

A smaller tire has higher rolling resistance than a larger tire at the same tire inflation pressure. According to Goodyear (2008), a smaller diameter drive axle tire results in an increase in engine RPMs, thereby increasing fuel consumption. TRB special report 286 (2006) indicates that tire or rim dimensions indeed have an influence on rolling resistance as tires with rim diameters of 15 inches or lower result in a 10% increase in rolling resistance compared to tires with a larger rim diameter.

Tire tread provides traction and makes contact with the road. The grooves of the tire are designed to channel water underneath the tire and prevent hydroplaning.

Generally, smooth treads roll better than coarse treads. In other words, a tire with thicker treads has a higher rolling resistance. Thicker tread tire can create more friction and noise, but its tradeoff is to enhance safety.

Different tire construction or tire types, under similar driving conditions, could result in different amounts of fuel consumed. The fuel economy improvement of radial ply tires over bias ply tires is well documented. A tire with radial ply construction has the advantage of relatively lower internal friction compared with that in a bias ply-constructed tire. Radial ply tire reduces the deformation of the tread in the contact patch. Therefore, these help decrease rolling resistance, tire wear, and energy consumption. Radial ply tires could improve gas mileage by at least 5% (Thompson, 1979) or more (Goodyear, 2008). A Canadian report exhibits that radial ply tires have a benefit in fuel economy of 10% or more over bias ply tires. However, a conservative figure generally accepted is that radial ply tires yield a 4 to 5% fuel economy benefit (Transportation Energy Management Program, 1982).

Using low-rolling-resistance tires help minimize energy consumed. Low-rolling-resistance tires are designed to enhance fuel economy by diminishing the amount of tire friction and resistance while driving. U.S. Department of Energy (2010b) estimates that about 5 to 15% of fuel consumed is used to overcome the rolling resistance for passenger cars, while for heavy trucks, the amount is as high as 15 to 30%. A Californian study (California Energy Commission, 2003) estimates that using low-rolling-resistance tires reduce fuel consumption by 1.5 to 4.5%, but the tire data were not sufficient to compare safety and other performance characteristics. New cars are generally equipped with low-rolling-resistance tires. Auto manufacturers typically equip new vehicles with tires that have low rolling resistance in order to satisfy Corporate Average Fuel Economy (CAFE) standards. Nevertheless, when it comes to replacing the tires, there are no requirements on adoption of low-rolling-resistance tires as the replacement tires.

The Daily Green (2009) provided interesting information on different low-rolling-resistance tires available in the market. Seven different low-rolling-resistance tires from Bridgestone, Goodyear, Michelin, and Yokohama were compared in terms of gas mileage, using a set of Goodyear Integrity radials as the control tires. Figure 2.2 illustrates the results. Among all tires examined, the fuel-efficient leader was Michelin Energy Saver A/S, which yielded 53.8 mpg. This is approximately a 4.7% improvement over Goodyear Integrity. Goodyear Assurance ComforTred had the least fuel economy, delivering only 50.0 mpg. Its fuel economy was worse than the control tires by 2.6%. The article did not, however, discuss why the Goodyear Integrity had been picked as the control tires. However, tire companies claimed the findings were different from their own test results. This could be because the test conditions were under different circumstances.

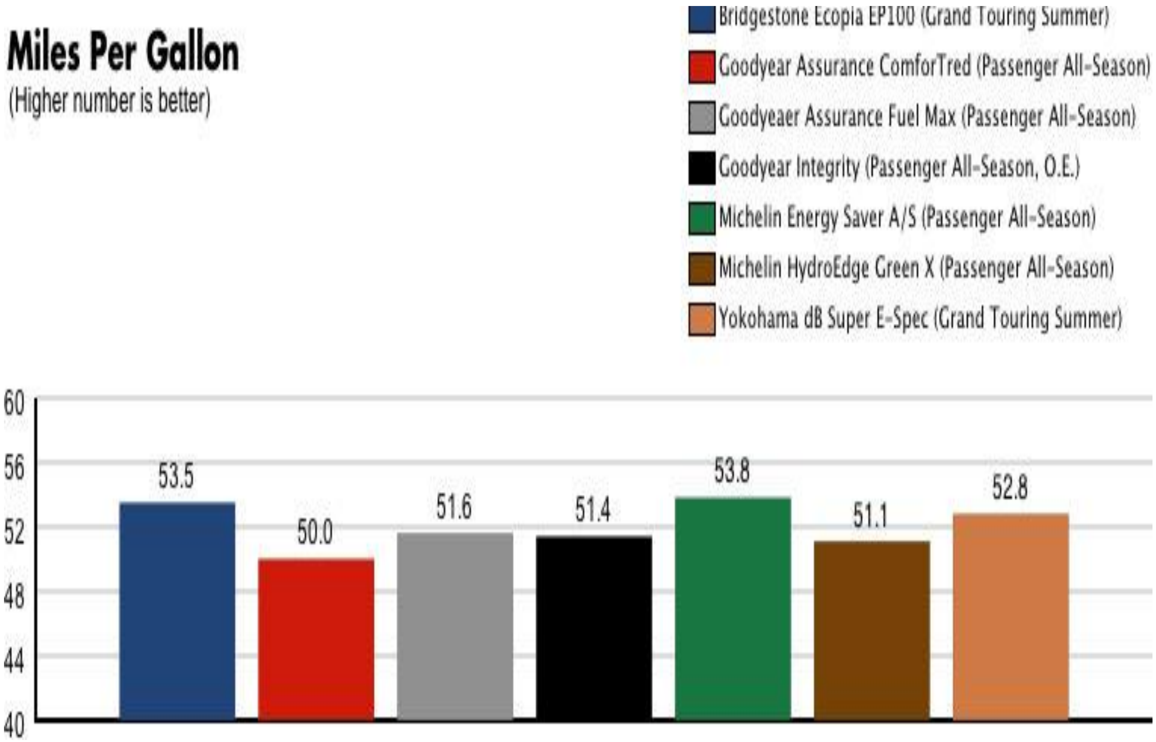


Figure 2.2 Fuel Economy of Different Tire Makers.

2.3.4 Aerodynamic Drag

Aerodynamic drag plays a part in fuel consumption due to the effect of wind and driving speed. Wind influences fuel economy by essentially changing the load to the vehicle. Side wind pushing the vehicle can affect rolling resistance. The driver must compensate by turning the steering wheel to the wind. The variable that most affects aerodynamic drag, however, is the vehicle speed. An aerodynamic drag loss mainly occurs at highway speeds and is much higher at highway speeds than at city driving speeds. At speeds of about 62 mph and above, over 50% of the fuel consumed to mobilize the vehicle is used to overcome the aerodynamic drag (Transportation Energy

Management Program, 1982). The U.S. EPA (1980) reports, based on estimates made by the Department of Transportation, that fuel consumed at a speed of 70 mph is 30% higher than fuel consumed at a speed of 40 mph. It also indicates that wind reduced fuel economy by 2 to 3% in most cars. However, the latter outcome is estimated based on a constant speed of 55 mph, which is in the range of highway speeds, and there is an implicit assumption that wind has no effect on fuel economy at vehicle speeds below 55 mph. The report indicates that the optimum fuel consumption is attained at the speed of around 35 to 40 mph for most cars.

2.3.5 Driving Practices and Techniques

Aside from vehicle factors mentioned earlier, driver behavior or the manner in which a vehicle is driven impacts fuel efficiency. While it is known that the factors influencing fuel consumption are acceleration rate, deceleration rate, and time spent on idling, the fuel economy information provided in some sources was limited to quantifying their effects (Energy and Environmental Analysis Inc., 2001). Not much research has been done on driving behavior. But it is reported that, by training drivers in fuel-efficient driving techniques, the fuel consumption could be reduced by 10 to 15% (Transportation Energy Management Program, 1982).

Aggressive driving is, among others, characterized by hard accelerations and decelerations. Driving with high rates of acceleration and deceleration could be represented as jackrabbits and tortoises, respectively. It is recommended that drivers should apply steady pressure rather than sudden push on the accelerator pedal for safety and fuel economy improvement (Transportation Energy Management Program, 1982).

Deceleration of vehicles is chiefly caused by slow moving traffic and traffic signals. The braking technique to improve fuel economy is to minimize brake usage. For example, when approaching slower moving traffic or traffic signals, begin to coast as soon as possible (Transportation Energy Management Program, 1982).

An idling engine does not provide useful work. Transportation Energy Management Program (1982) indicates that every 4 minutes of idling consumes enough fuel to move a typical car about 0.63 miles (1 km). An idling time of 10 seconds uses more fuel than the vehicle uses to restart and replace the electrical energy. Therefore, trips being made should be planned in terms of route selection and other factors in order to minimize the number of stops.

The effect on vehicular fuel consumption depends on several aspects as mentioned earlier. It also includes usage of auxiliary devices, as energy is required to power accessory loads. Figure 2.3 summarizes the major energy components in urban driving.

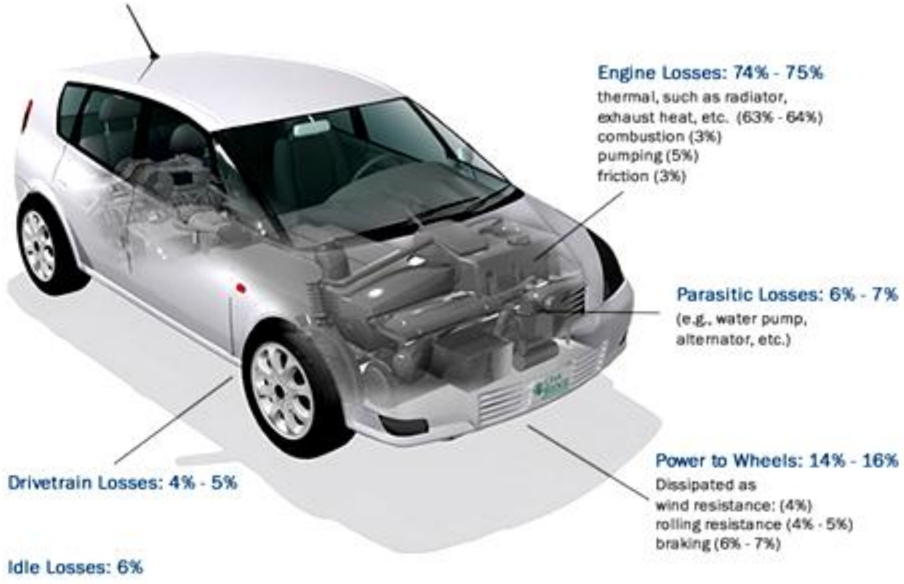


Figure 2.3 Energy Requirement for City Driving (U.S. Department of Energy, 2011).

2.4 Overview of Costs in Life-Cycle Cost Analysis

To evaluate the economic worth of various pavement projects, an analysis should be made in order to select the potential design alternatives. Life-cycle cost analysis (LCCA) is an economic evaluation technique which aims at considering all significant costs incurred in the project life (or analysis period). It is expressed in terms of monetary value.

The use of LCCA is traced back to an 1847 study by Gillespie (Peterson, 1985) to characterize the most economic highway project. In 1984, the National Cooperative Highway Research Program (NCHRP) had a project to promote LCCA. The American Association of State Highway and Transportation Officials (AASHTO) recommended the use of LCCA in the Pavement Design Guides of 1983 and 1993 as a decision support tool for economic evaluation. The Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991 was the first act which called for "the use of LCCA in the design and engineering of bridges, tunnels, and pavements" both for metropolitan and statewide planning. Afterward, the National Highway System (NHS) Designation Act of 1995 mandated States to perform LCCA on NHS projects costing $25 million or more. In 1996, the Federal Highway Administration (FHWA) released LCCA guidance. Later, the Transportation Equity Act for the 21st Century (TEA-21) of 1998 repealed the requirement to perform LCCA on NHS projects. Guidance and recommendations on practices in conducting LCCA was distributed by the FHWA in 1998 as Life-Cycle Cost Analysis in Pavement Design. Recently, the FHWA's Office of Asset Management has developed an LCCA-based software package for pavements (Ozbay et al., 2003).

Life-cycle costs include all costs anticipated over the intended service life of a project or a facility. The basic theory of LCCA is that all the impacts of the project can be converted to monetary values so that the comparison between alternatives can be conducted directly. The costs included in LCCA can be tangible and intangible and can be generated by the agency, by the users of the facility, or by society (Ozbay et al., 2003). The costs incorporated in LCCA are illustrated in Figure 2.4.

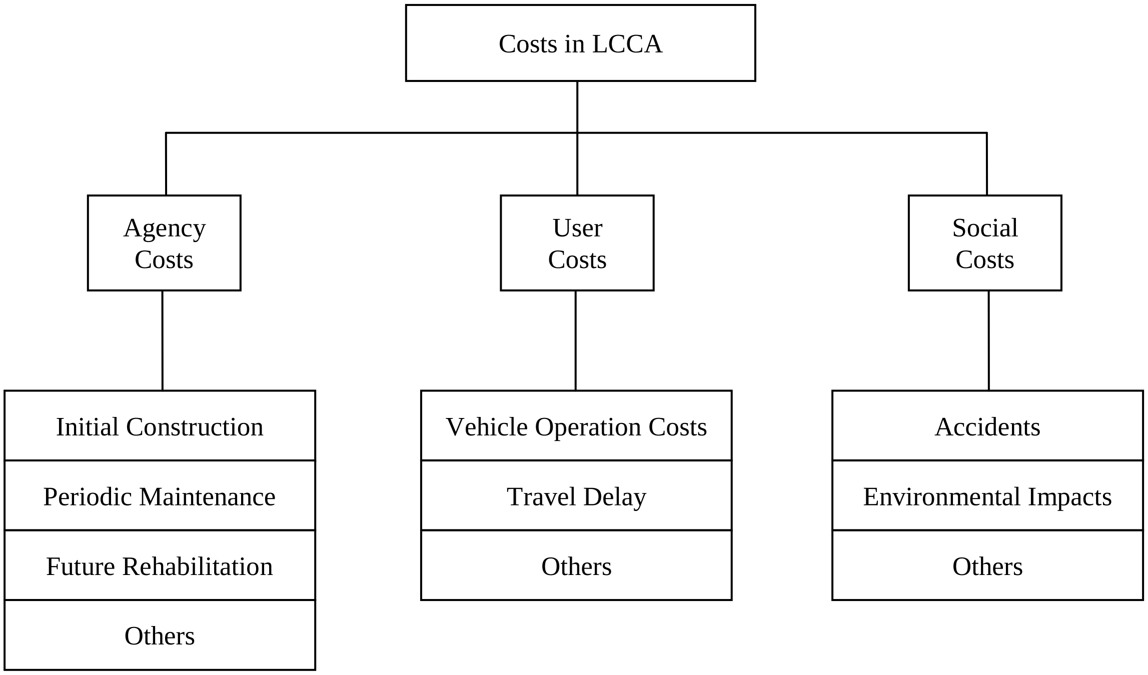


Figure 2.4 Costs in LCCA for Transportation Projects.

2.4.1 Agency Costs

Agency costs are the costs incurred directly by the agency in order to put the project or the facility in service. Agency costs comprise initial construction cost, future routine and preventive maintenance costs, resurfacing and rehabilitation cost, and costs inherently associated with using personnel, for example, contract administration, construction supervision, and administrative costs. The initial construction, periodic maintenance, and rehabilitation costs include the costs of materials, labor, machinery, and other contingencies. The salvage value is also considered as a part of agency costs. It is the remaining value of the project at the end of the analysis period or service life. Salvage value is a negative impact when calculating net present value, the discounted salvage is subtracted from the total costs. There is no general agreement on how to estimate the salvage value since most infrastructure projects are not demolished at the end of their service life or analysis period. Therefore, if the serviceability remains the same among alternatives, the salvage value can be omitted from the calculations (Ozbay et al., 2003).

2.4.2 User Costs

User costs are the costs incurred by the project users. These costs occur throughout the service life of the project. According to Huang (2004), for a highway facility, the user costs include both apparent and hidden costs incurred by the motoring public. Most user costs are intangible. These costs include vehicle operating costs, user travel delay, and other components such as discomfort from traffic flow interruptions and traffic noise. Costs of travel delay are dependent on the demand and capacity of the facility. During work zone operations and rehabilitation activities, travel delay costs depend on a number of factors, such as traffic volume, number of days in operation, time of day of operation, and number of lanes closed.

Vehicle operating costs depend on the facility's serviceability, that is, mainly pavement roughness. These costs consist of fuel consumption, lubricant consumption, tire wear, parts and labor costs, vehicle maintenance, and depreciation or resale value. Vehicle operating costs can be categorized into fixed and variable costs as depicted in Figure 2.5 by the Victoria Transport Policy Institute. Roughness is a pavement characteristic that could influence fuel consumption. There are significant operating cost differences between a smooth and rough pavement. Vehicle operating costs, especially fuel consumption, increase with an increase of pavement roughness (Peterson, 1985). A recent research project that will be published in the near future by Auburn University also presents the effect of pavement smoothness on fuel consumption (Christie, 2011). A preview of the study shows that improvement in pavement smoothness could lower fuel consumption by 1.8 to 2.7%. Consequently, the amount of fuel savings would be about 3.3 billion gallons a year.

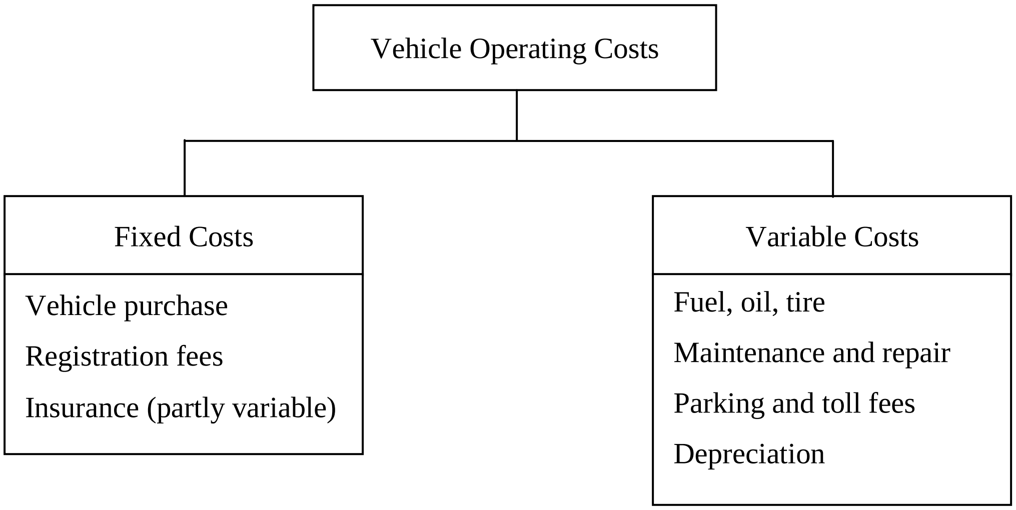


Figure 2.5 Components of Vehicle Operating Costs.

2.4.3 Social Costs

Social costs are the costs encountered by society. The social costs include the costs of crashes, accidents, property damage, and environmental impact. Accident costs could be estimated as a dollar per unit length for different types of facilities, such as rural, urban, and freeway. Generally, there is no research showing that accident rates can vary among the alternatives with different serviceability. The environmental impacts can encompass air, water, noise, and natural resources. Only the costs from air and noise pollution could be monetized in transportation evaluation (Ozbay et al., 2003).

In summary, studies have shown that there are several important factors influencing vehicular fuel consumption. Vehicle weight, engine oil, and tires are the examples caused by the vehicle itself. Drivers' behavior and techniques also have an impact on fuel consumption.

LCCA is a technique that employs the principles of economic analysis to evaluate long term performance between competing alternative investment options. Its purpose is to estimate the overall costs of the project alternatives and to select the facility that provides the lowest overall costs. LCCA is performed by adding up the discounted monetary values of all benefits and costs that incur in each alternative. Costs considered in the LCCA include the costs of owning and operating the facility over a period of time.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Introduction

In order to examine any differences that might exist in vehicular fuel consumption on PCC versus AC pavements under city driving conditions, the study relies on operating an instrumented motor vehicle on city streets. The fuel consumption of a test vehicle on different surface types is then collected and compared. This chapter describes selection of road sections, test vehicle, data collection, and data analysis approach.

3.2 Selection of Road Sections

Four street sections (two asphalt and two concrete sections) were selected for fuel consumption studies. The selection criteria included surface material type, surface roughness, longitudinal gradient, and location of the pavement sections. Two sets of concrete pavement versus asphalt pavement sections with similar surface roughness and longitudinal gradient were accordingly selected. Each pair of road sections (one AC and one PCC) was approximately parallel so as to minimize the effect of wind direction and velocity during measurement runs on the two road sections at a given time. Below is a detailed description of each roadway section selected.

3.2.1 The First Test Sites

3.2.1.1 The PCC Section

A PCC section chosen was Abram Street (Figure 3.1). This is a Continuously Reinforced Concrete Pavement (CRCP). The reinforced concrete slab is 8 inches deep over 2-inch hot mix asphalt concrete type D on an 8-inch lime stabilized subgrade. The roughness measurements were done by the Texas Department of Transportation resulting in an average International Roughness Index (IRI) measurement of 174.6 in/mile. The length of this section is approximately 3,500 feet. The longitudinal gradient was uphill with the average value of 1.2% in the eastbound direction (direction of observations).

3.2.1.2 The AC Section

Approximately two blocks away and parallel to the PCC section, Pecandale Drive (Figure 3.2) was selected as a test section for the asphalt pavement. Its layers includes a 7-inch deep hot mix asphalt concrete (1.5-inch Type D and 5.5-inch Type B) on a 6-inch lime stabilized subgrade. The average IRI measurement was measured to be 180.6 in/mile. Comparing with the PCC section, the average IRI values are 3% higher. However, they are both in the IRI range for new pavements (Sayers and Karamihas, 1998). The length of the section is approximately 1,900 feet. The average longitudinal gradient was +1.2% in the direction of observations (eastbound), which was identical to the gradient of the PCC section.

Figure 3.1 Abram Street (PCC).

Figure 3.2 Pecandale Drive (AC).

3.2.2 The Second Test Sites

Although asphalt pavements typically have high skid resistance, this study did not have the skid resistance on the first two pavement sections measured due to lack of testing devices. Therefore, statistical comparison of fuel consumption is needed to test separately on other random selected sections to investigate whether or not the results are consistent with the first sites.

3.2.2.1 The PCC Section

The second PCC section was the Road to Six Flags Street (Figure 3.3). This section is a Jointed Plain Concrete Pavement (JPCP) with a 7-inch concrete slab on a 6-inch lime stabilized subgrade. The spacing of the transverse joints was 20 feet. The average IRI value was measured to be 323.3 in/mile. The length of the road section is approximately 1,600 feet. The average longitudinal gradient was +0.4% in the direction of observations (westbound).

3.2.2.2 The AC Section

The asphalt pavement section selected was the Randol Mill Road (Figure 3.4). It consisted of an 8-inch deep layer of hot mix asphalt concrete (2-inch Type D and 6-inch Type A) on a 6-inch lime stabilized subgrade. The average IRI value was 276.7 in/mile. The IRI values of the last two sections have a difference of 16.8%, with the asphalt section having a smaller IRI (smoother). The length of this section is approximately 1,400 feet. The average longitudinal gradient was uphill at the rate of 0.6% in the direction of observations (westbound).

Figure 3.3 Road to Six Flags Street (PCC).

Figure 3.4 Randol Mill Road (AC).

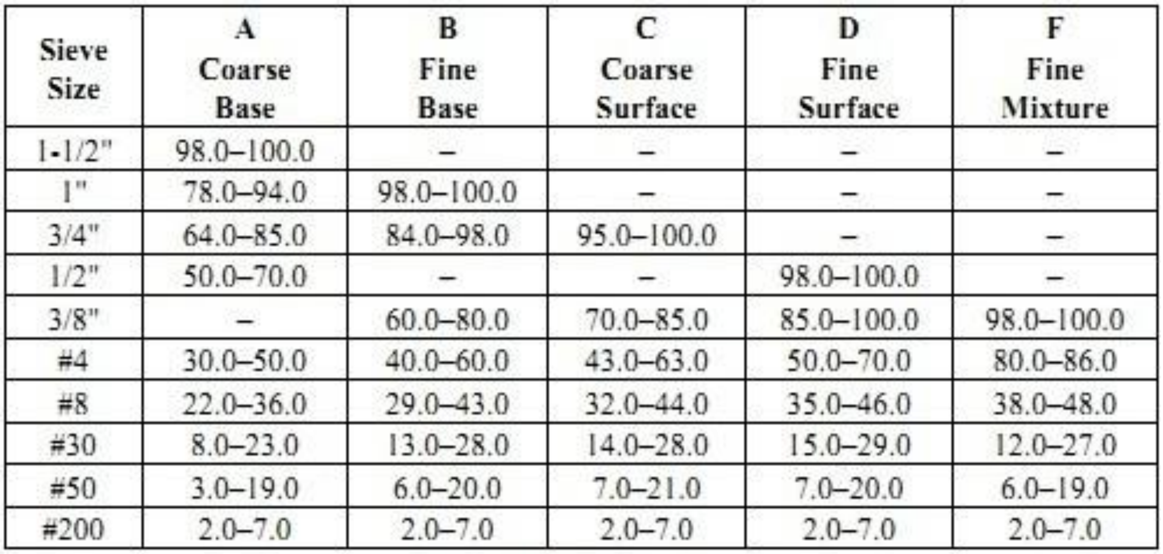
Table 3.1 summarizes the test section characteristics in terms of pavement types, roughness indices, and longitudinal grades. The details regarding the IRI measurements for each test section are provided in Appendix A. Appendix B shows the longitudinal profile surveys performed for each test section.

Table 3.1 Road Section Characteristics

	Road Section	Pavement Type	Details	Approx. Length of Section (ft)	Average IRI (in/mi)	Longitudinal Slope in Data Collection Direction (%)
First Test Sites	Abram Street	PCC (CRCP)	8" continuously reinforced concrete over 2" HMAC type D on 8" lime stabilized subgrade	3,500	174.6	+1.2
	Pecandale Drive	AC (HMA)	7" HMAC (1.5" Type D, 5.5" Type B) on 6" lime stabilized subgrade	1,900	180.6	+1.2
Second Test Sites	Road to Six Flags Street	PCC (JPCP)	7" reinforced concrete on 6" lime stabilized subgrade 20’ transverse joint spacing	1,600	323.3	+0.4
	Randol Mill Road	AC (HMA)	8" HMAC (2" Type D, 6" Type A) on 6" lime stabilized subgrade	1,400	276.7	+0.6

The City of Arlington has adopted Texas Department of Transportation specifications for public works. That is the Standard Specifications for Construction and Maintenance of Highways, Streets, and Bridges. Surface type A, B, and D of asphalt pavements conform to the gradations of materials shown in Table 3.2. The specifications are outlined under 300 Items of Surface Courses and Pavement, located in Article 340.4 and Section A.1 (Texas Department of Transportation, 2004).

Table 3.2 Gradations (% Passing by Weight or Volume)



Sieve Size	A Coarse Base	B Fine Base	C Coarse Surface	D Fine Surface	F Fine Mixture
1-1/2"	98.0–100.0	–	–	–	–
1"	78.0–94.0	98.0–100.0	–	–	–
3/4"	64.0–85.0	84.0–98.0	95.0–100.0	–	–
1/2"	50.0–70.0	–	–	98.0–100.0	–
3/8"	–	60.0–80.0	70.0–85.0	85.0–100.0	98.0–100.0
#4	30.0–50.0	40.0–60.0	43.0–63.0	50.0–70.0	80.0–86.0
#8	22.0–36.0	29.0–43.0	32.0–44.0	35.0–46.0	38.0–48.0
#30	8.0–23.0	13.0–28.0	14.0–28.0	15.0–29.0	12.0–27.0
#50	3.0–19.0	6.0–20.0	7.0–21.0	7.0–20.0	6.0–19.0
#200	2.0–7.0	2.0–7.0	2.0–7.0	2.0–7.0	2.0–7.0

3.3 The Test Vehicle

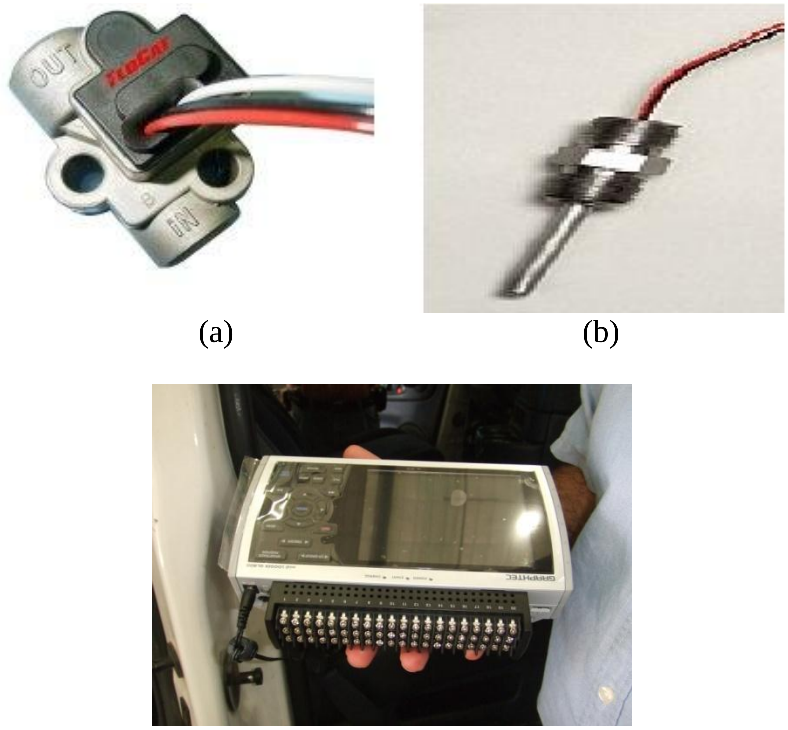
An instrumented model 2000 Chevy Astro van (Figure 3.5) was utilized as the test vehicle. Fuel consumption measurements in gallons per mile (gpm) were made with an on-board data acquisition system. The fuel sensor, the temperature sensors, and the data acquisition system (shown in Figure 3.6) were connected to the engine as shown schematically in Figure 3.7. Two fuel sensors made instantaneous measurements of the amount of fuel entering the engine and returning to the tank, with the difference between the fuel intake and the amount returned to the tank being the instantaneous of fuel consumed. The temperatures of the fuel entering the engine and returning to the tank were also measured using two temperature gauges. The data acquisition system probes could collect a sample from the sensors every 100 or 200 millisecond as setting by the user. In addition to the fuel amounts and fuel temperature, the data acquisition system also recorded the instantaneous vehicle speed. Vehicle speed is sampled at the rate of one second driven by the transmission shaft.

The test vehicle has the curb weight of 4,397 lbs, which is the total weight of vehicle with standard equipment. Its maximum allowable total vehicle weight, including the weight of passengers and cargo (gross vehicle weight rating, GVWR) is 6,100 lbs. According to the U.S. Environmental Protection Agency (EPA) vehicle classifications (28 vehicle classes) listed in Table 3.3, the test vehicle is categorized into Light-Duty Gasoline Truck 3 (LDGT3) as its GVWR was within this range. The LDGT3 class when fully loaded has an average vehicle weight of 7,500 lbs. On the contrary, vehicle weight is not a criterion for vehicle classification in the Federal Highway Administration (FHWA). FHWA separates vehicle types into 13 categories based on whether the vehicle carries passengers or cargo. Non-passenger vehicles are further divided by number of axles and number of units, including both power and trailer units (Federal Highway Administration, 2011).

(a)

(b)

Figure 3.5 The Test Van and Data Collection Set-Up. (a) The Instrumented 2000 Chevy Astro Van and (b) The Inside Set-Up during Data Collection.



(a) (b)

(c)

Figure 3.6 On-Board Instruments. (a) Fuel Meter (b) Temperature Gauge and (c) Data Acquisition System.

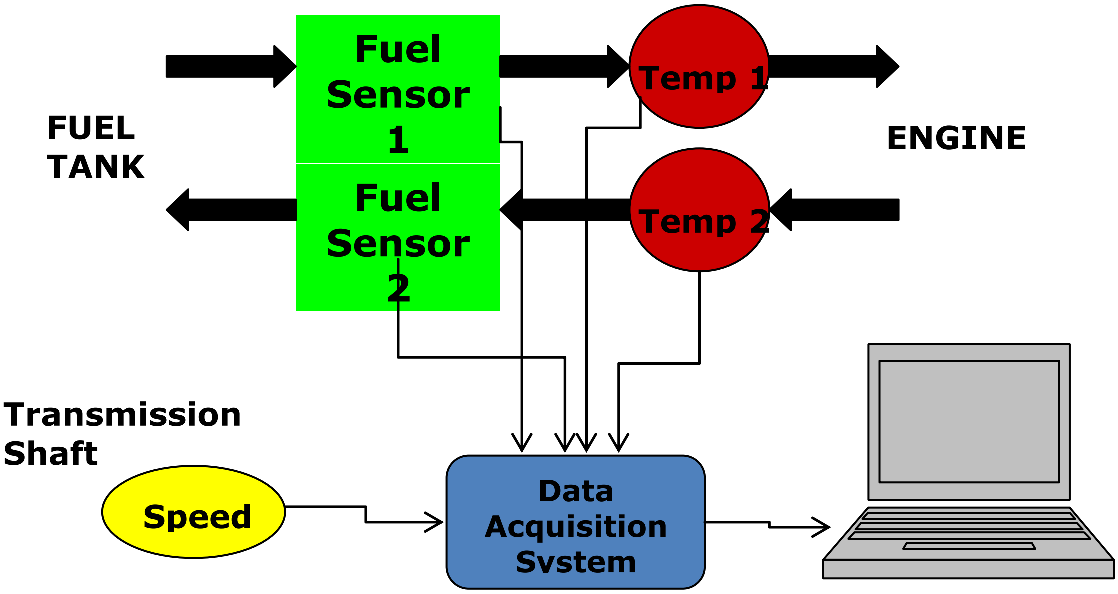
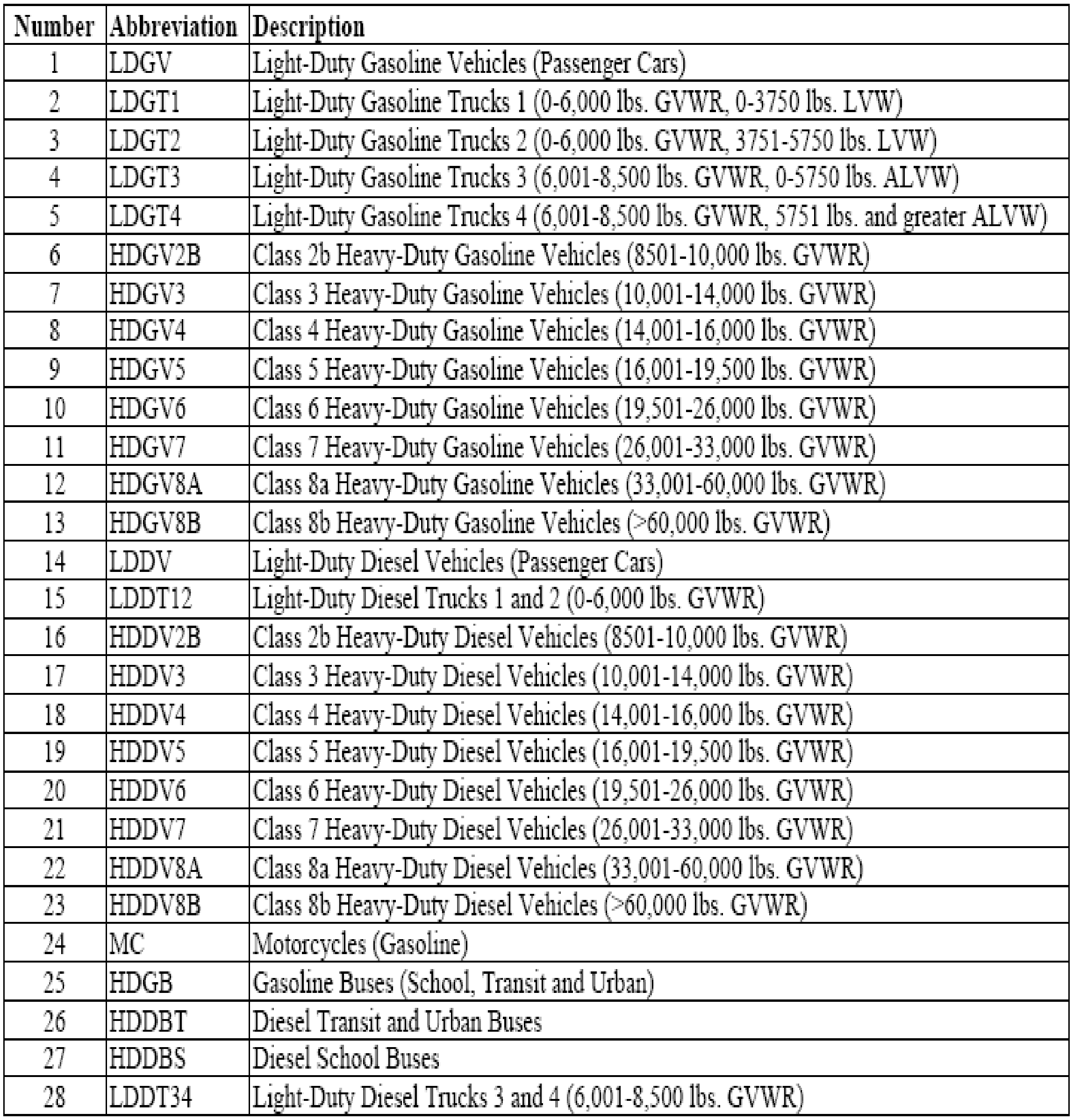


Figure 3.7 Schematic Diagram of the Sensor and the Data Acquisition System.

Table 3.3 Vehicle Classification by U.S. Environmental Protection Agency (2003)



Number	Abbreviation	Description
1	LDGV	Light-Duty Gasoline Vehicles (Passenger Cars)
2	LDGT1	Light-Duty Gasoline Trucks 1 (0-6,000 lbs. GVWR, 0-3750 lbs. LVW)
3	LDGT2	Light-Duty Gasoline Trucks 2 (0-6,000 lbs. GVWR, 3751-5750 lbs. LVW)
4	LDGT3	Light-Duty Gasoline Trucks 3 (6,001-8,500 lbs. GVWR, 0-5750 lbs. ALVW)
5	LDGT4	Light-Duty Gasoline Trucks 4 (6,001-8,500 lbs. GVWR, 5751 lbs. and greater ALVW)
6	HDGV2B	Class 2b Heavy-Duty Gasoline Vehicles (8501-10,000 lbs. GVWR)
7	HDGV3	Class 3 Heavy-Duty Gasoline Vehicles (10,001-14,000 lbs. GVWR)
8	HDGV4	Class 4 Heavy-Duty Gasoline Vehicles (14,001-16,000 lbs. GVWR)
9	HDGV5	Class 5 Heavy-Duty Gasoline Vehicles (16,001-19,500 lbs. GVWR)
10	HDGV6	Class 6 Heavy-Duty Gasoline Vehicles (19,501-26,000 lbs. GVWR)
11	HDGV7	Class 7 Heavy-Duty Gasoline Vehicles (26,001-33,000 lbs. GVWR)
12	HDGV8A	Class 8a Heavy-Duty Gasoline Vehicles (33,001-60,000 lbs. GVWR)
13	HDGV8B	Class 8b Heavy-Duty Gasoline Vehicles (>60,000 lbs. GVWR)
14	LDDV	Light-Duty Diesel Vehicles (Passenger Cars)
15	LDDT12	Light-Duty Diesel Trucks 1 and 2 (0-6,000 lbs. GVWR)
16	HDDV2B	Class 2b Heavy-Duty Diesel Vehicles (8501-10,000 lbs. GVWR)
17	HDDV3	Class 3 Heavy-Duty Diesel Vehicles (10,001-14,000 lbs. GVWR)
18	HDDV4	Class 4 Heavy-Duty Diesel Vehicles (14,001-16,000 lbs. GVWR)
19	HDDV5	Class 5 Heavy-Duty Diesel Vehicles (16,001-19,500 lbs. GVWR)
20	HDDV6	Class 6 Heavy-Duty Diesel Vehicles (19,501-26,000 lbs. GVWR)
21	HDDV7	Class 7 Heavy-Duty Diesel Vehicles (26,001-33,000 lbs. GVWR)
22	HDDV8A	Class 8a Heavy-Duty Diesel Vehicles (33,001-60,000 lbs. GVWR)
23	HDDV8B	Class 8b Heavy-Duty Diesel Vehicles (>60,000 lbs. GVWR)
24	MC	Motorcycles (Gasoline)
25	HDGB	Gasoline Buses (School, Transit and Urban)
26	HDDBT	Diesel Transit and Urban Buses
27	HDDBS	Diesel School Buses
28	LDDT34	Light-Duty Diesel Trucks 3 and 4 (6,001-8,500 lbs. GVWR)

3.4 Data Collection

3.4.1 Experimental Design

The test vehicle equipped with the precision fuel meters and the speedometer was driven over the experimental dry-surface road sections. Each PCC and AC section pair had similar gradient and roughness indices. At this stage, the experimental design has two factors (pavement type and driving mode) and two levels for each factor (PCC versus AC; and constant speed of 30 mph versus a 3 mph/sec acceleration mode). The two factors and two levels are varied together yielding four (2^2) treatment combinations or responses on each pair of road sections, as shown in Table 3.4.

Table 3.4 The Four Factor-Level Combinations

Factor-Level Combination	Pavement Type	Driving Mode
1	PCC	Constant Speed
2	PCC	Acceleration
3	AC	Constant Speed
4	AC	Acceleration

3.4.2 Sample Sizes

The main objective of this study is to investigate any differences that might exist in fuel consumption when operating a motor vehicle on an AC versus a PCC pavement under constant speed and acceleration driving conditions. Previously published studies did not provide any evidence of the statistical parameters, for example, standard deviations, in such fuel consumption studies. Therefore, some initial fuel measurements were carried out on the experimental road sections and the preliminary data was retrieved.

From the data collected, the sample sizes are calculated individually for constant speed and acceleration scenarios as the fuel consumption observed between these driving modes were different. Regardless of the pavement type, the fuel consumption operating under acceleration was observed to be higher than under constant speed. Hence, this is considered as a single-factor study.

In planning an experiment, the sample sizes that need to be taken on each treatment are crucial. If the numbers of observations are too few, the experiment's outcome may be statistically indecisive. If there are too many observations taken, it is time-consuming and costly. In sample-size determination with power approach, the study uses a power of the test of 0.90, which can be interpreted as there is a probability of 90%, based on sample sizes employed, that the results will lead to the detection of differences in fuel consumption.

From the preliminary data on Pecandale and Abram streets, the study has yielded standard deviations of 5.8 $x10^{-3}$ gpm under constant speed and 13.2 $x10^{-3}$ gpm under acceleration conditions, whereas on Randol Mill and Road to Six Flags streets, the standard deviations are 5.3 $x10^{-3}$ gpm under constant speed and 11.5 $x10^{-3}$ gpm under acceleration conditions, respectively. Table 3.5 depicts the specifications employed in the study – 10% level of significance and 90% power. *r* is the number of factor levels (i.e., AC and PCC), Δ is the minimum range in fuel consumption investigated, and *n* is the sample size.

Table 3.5 Sample-Size Determination

	Pecandale (AC) vs. Abram (PCC)		Randol Mill (AC) vs. Six Flags (PCC)	
	Constant Speed	Acceleration	Constant Speed	Acceleration
α	0.10	0.10	0.10	0.10
$1-\beta$	0.90	0.90	0.90	0.90
r	2	2	2	2
σ (x10^{-3} gpm)	5.8	13.2	5.3	11.5
max (x10^{-3} gpm)	55.7	264.4	53.7	262.1
min (x10^{-3} gpm)	40.7	224.9	41.1	233.2
Δ (x10^{-3} gpm)	10.0	25.0	10.0	25.0
n	7	7	7	6

As mentioned earlier, if numbers of observations are too few, the experiment may be inconclusive. Too many observations could be costly and time-consuming. The study was investigated the statistical significance at a minimum range of at least 10.0 x10^{-3} gpm for constant speed and 25.0 x10^{-3} gpm for acceleration driving conditions in order to detect differences with high probability. Using Table 3.6 (Kutner et al., 2005), the appropriate sample sizes are determined to be 6 or 7 observations. However, equal sample sizes of 7 are preferred for the ease of analysis when pair comparisons are to be done, as is the case here.

Table 3.6 Sample-Size Determination Table

Power $1-\beta=.90$

	$\Delta/\sigma=1.0$				$\Delta/\sigma=1.25$				$\Delta/\sigma=1.50$				$\Delta/\sigma=1.75$				$\Delta/\sigma=2.0$				$\Delta/\sigma=2.5$				$\Delta/\sigma=3.0$			
	α				α				α				α				α				α				α			
r	.2	.1	.05	.01	.2	.1	.05	.01	.2	.1	.05	.01	.2	.1	.05	.01	.2	.1	.05	.01	.2	.1	.05	.01	.2	.1	.05	.01
2	14	18	23	32	9	12	15	21	7	9	11	15	5	7	8	12	4	6	7	10	3	4	5	7	3	3	4	6
3	17	22	27	37	11	15	18	24	8	11	13	18	6	8	10	13	5	7	8	11	4	5	6	8	3	4	5	6
4	20	25	30	40	13	16	20	27	9	12	14	19	7	9	11	15	6	7	9	12	4	5	6	8	3	4	5	6
5	21	27	32	43	14	18	21	28	10	13	15	20	8	10	12	15	6	8	9	12	4	5	6	9	4	4	5	7
6	22	29	34	46	15	19	23	30	11	14	16	21	8	10	12	16	7	8	10	13	5	6	7	9	4	4	5	7
7	24	31	36	48	16	20	24	31	11	14	17	22	9	11	13	17	7	9	10	13	5	6	7	9	4	5	5	7
8	26	32	38	50	17	21	25	33	12	15	18	23	9	11	13	17	7	9	11	14	5	6	7	9	4	5	6	7
9	27	33	40	52	17	22	26	34	13	16	18	24	9	12	14	18	8	9	11	14	5	6	8	10	4	5	6	7
10	28	35	41	54	18	23	27	35	13	16	19	25	10	12	14	19	8	10	11	15	5	7	8	10	4	5	6	7

A day to be selected for data collection is mainly based on the surface condition of the pavements. The surfaces must be dry. It would be on a dry day without rain. On each dry day, other ambient conditions such as the direction and magnitude of wind speed, air temperature, and humidity, were recorded. However, they did not influence the analysis since pairwise data are collected under the same ambient conditions.

3.4.3 Measurements of Fuel Consumption

As mentioned earlier, fuel consumption measurements were made on four city street sections: two PCC and two AC. Each PCC and AC section pairs had similar gradient and roughness indices. In addition to pavement type, a number of other factors could affect fuel consumption, including speed, acceleration, gradient, pavement roughness, ambient temperature, atmospheric pressure, wind speed and direction, vehicle weight, tire pressure, and use of auxiliary devices in the vehicle. In order to isolate the effect of pavement type or fuel consumption, all the above factors were either controlled, or assumed to be the same during the measurement runs.

The variables recorded for each measurement run included:

- Ambient air temperature
- Humidity
- Wind speed and direction
- Vehicle weight
- Tire pressure
- On/off status of auxiliary devices (A/C, radio, headlights, windows, etc.)

The last three factors were controlled and kept the same for all runs, during data collection. The information on the first three factors was obtained from National Oceanic and Atmospheric Administration (NOAA)'s National Weather Service website, www.weather.gov, at the time of each study run. The weather station site is in Arlington Municipal Airport. The radial distance from weather site to study sites is approximately 6 miles.

A 2000 Chevy Astro van with a six-cylinder 190-hp engine and automatic transmission was used. For data collection, the vehicle is fitted with a data acquisition system. The test vehicle, including a full tank of gasoline, all test equipment, and two occupants, was approximately 4,700 lbs. The curb weight was 4,397 lbs.

Prior to the data collection on each study day, gasoline was at the full level in order to control vehicle weight. The tire pressure was ascertained to be 50 psi, and the vehicle was warmed up for about 15 minutes.

Prior to the commencement of a test run, the road section to drive on first was randomly selected by tossing a coin (head for AC and tail for PCC). The next road section would be its pair. For example, on a given day, a coin showed head, then the first road section to perform fuel measurement would be on an asphalt section. Each of four road sections was driven three consecutive runs at constant speed and then three consecutive runs under acceleration. An observer, who rode with the driver, captured the fuel data while the vehicle was operated at constant speed and under acceleration. Fuel temperature, power cord, and instrument wires were periodically monitored to verify that they worked properly.

During the performance of fuel measurement runs, obstacles occasionally occurred and interrupted the driving conditions. Constant speed condition could not be maintained and the acceleration driving condition could not be achieved. These caused the driver to abandon these runs. Consequently, those runs had to be repeated. Apart from unexpected traffic congestion and roadside maintenance, other data collection interferences included previously parked vehicles pulling into the driving lane, mail delivery vehicles stopping and going in the direction of observation, tailgating with relatively low speed road users such as cyclists, pedestrians and lawn mowing near the road curb, etc.

As discussed earlier, the fuel consumption data was collected for a total of seven days. The fuel measurement data collection plan is depicted in Table 3.7. A and B represent an average fuel consumption rate in gallons per mile under constant speed and acceleration conditions for the first test sites, respectively. Likewise, C and D represent an average fuel consumption rate in gallons per mile under constant speed and acceleration conditions for the second test sites, respectively. Within each pair of test sites, a statistical test to compare the means is employed on each pair of fuel consumption under the same driving condition. For instance, considering the first test sites, fuel consumption at constant speed on Abram Street (A_1) is compared with fuel consumption at constant speed on Pecandale Drive (A_2). Again, under the acceleration driving condition, fuel consumption B_1 on Abram Street is compared with fuel consumption B_2 on Pecandale Drive. The same approach is also adopted for the second test sites.

Table 3.7 Fuel-Consumption Measurement

Day	Fuel Consumption Measurement							
	The First Test Sites				The Second Test Sites			
	Abram Street (PCC)		Pecandale Drive (AC)		Road to Six Flags (PCC)		Randol Mill Road (AC)	
	Constant Speed	Accel.	Constant Speed	Accel.	Constant Speed	Accel.	Constant Speed	Accel.
Day 1	A_1	B_1	A_2	B_2	C_1	D_1	C_2	D_2
Day 2	A_1	B_1	A_2	B_2	C_1	D_1	C_2	D_2
Day 3	A_1	B_1	A_2	B_2	C_1	D_1	C_2	D_2
Day 4	A_1	B_1	A_2	B_2	C_1	D_1	C_2	D_2
Day 5	A_1	B_1	A_2	B_2	C_1	D_1	C_2	D_2
Day 6	A_1	B_1	A_2	B_2	C_1	D_1	C_2	D_2
Day 7	A_1	B_1	A_2	B_2	C_1	D_1	C_2	D_2

3.5 Data Analysis Approach

As discussed, a sample size of seven is determined to be adequate for each factor–level combination in order to obtain statistically meaningful conclusions at a 90% level of confidence. A paired t-test is a pairwise comparison test used when comparing two sets of measurements to assess whether the means are statistically different. As a result, it is utilized as the statistical tool for hypothesis testing purposes in comparing fuel consumption differences between the two pavement types in each driving mode.

Relating vehicle weight to fuel consumption, the test vehicle is extrapolated to other vehicle classes in the mix. This enables the study to develop a spreadsheet format to estimate the total fuel savings for different pavement types.

CHAPTER 4

DATA ANALYSIS AND RESULTS

4.1 Introduction

In the course of the fuel consumption measurements, every attempt was made to either control all other factors that could affect fuel consumption or keep the factors that cannot be controlled the same. These included 1) vehicle weight, 2) tire pressure, 3) fuel type, 4) ambient temperature, 5) humidity, and 6) wind speed and direction. Among these factors, the first three were kept the same for all runs. Factors 4-6 were recorded for each run so that pairwise comparisons of fuel consumption on different pavements would be made under similar conditions. For example, it would not be appropriate to compare fuel consumption on the asphalt section when there is a 20 mph headwind to that on the concrete pavement when there is a tailwind. Also, fuel consumption characteristics of a vehicle could be different under different temperature or humidity conditions.

Two different driving modes (cruise vs. acceleration) were used in the test runs. Under the constant speed mode, a cruise speed of 30 mph was maintained throughout the test run. In the acceleration mode, the fuel consumption data were collected while accelerating from zero to 30 mph in 10 seconds, yielding an average acceleration rate of 3 mph/second.

Each data collection session included multiple runs in one or another driving mode along two parallel test sites, one AC and one PCC. After each measurement session, the fuel flow rate in gallons per minute and the cumulative fuel consumed in each scenario were retrieved from the on-board data acquisition system. Two examples of the raw data plots are shown in Figure 4.1 for PCC at constant speed and in Figure 4.2 for PCC under the acceleration mode. Vehicle speed is measured directly by the vehicle speed sensor system mounted on the shaft. As the shaft rotates at various speeds, magnetic field is induced by generating voltage pulse corresponding to those speeds. The vehicle speed sensor generates an AC voltage signal output that increases or decreases proportionally with the vehicle speed.

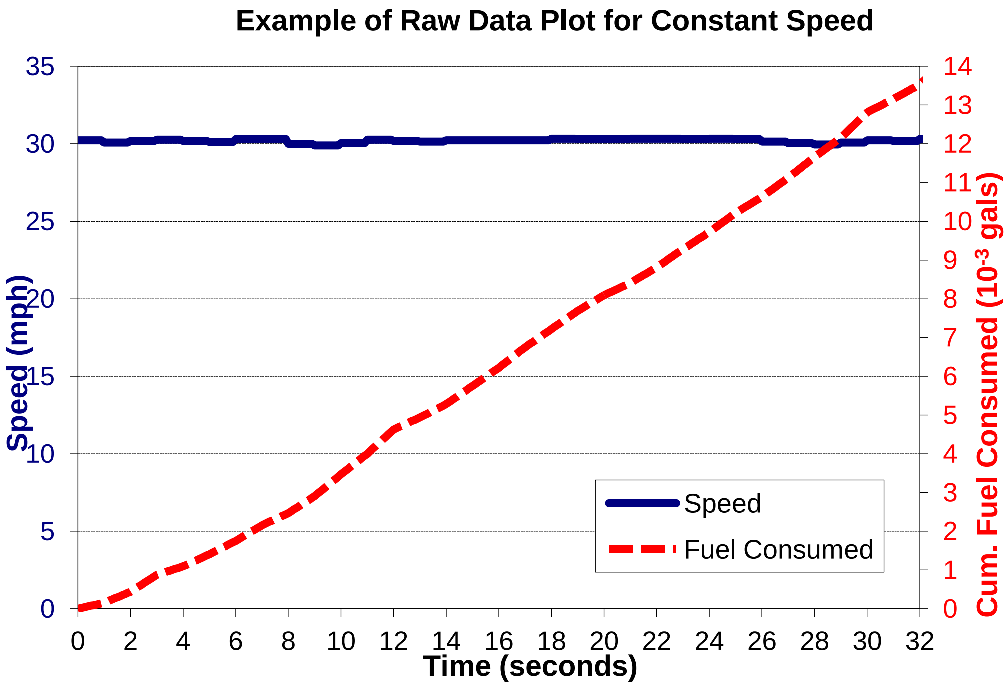


Figure 4.1 Example of Raw Data Plot for PCC Pavement under Constant Speed Mode

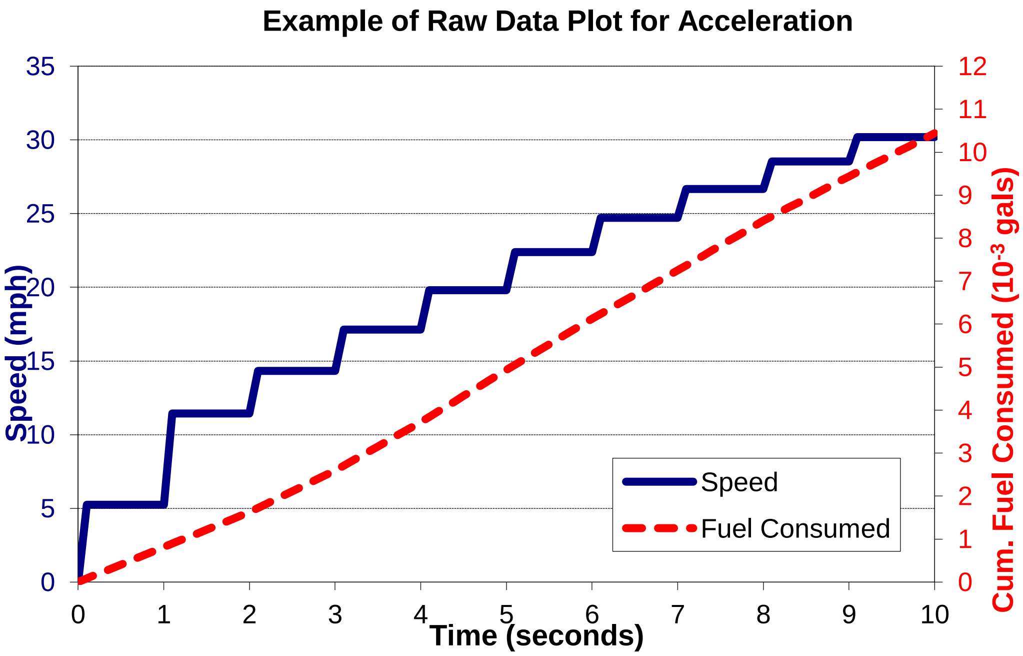


Figure 4.2 Example of Raw Data Plot for PCC Pavement under Acceleration Mode

4.2 Statistical Comparisons

The data are tested at a 10% level of significance in order to obtain statistically meaningful conclusions. To compare fuel consumption of an instrumented test vehicle as a function of pavement surface types, a paired t-test is carried out. The *p*-value is also considered when investigating.

4.2.1 Paired t-Test

As mentioned, a paired t-test is a pair test used when comparing two sets of measurements to assess whether the means are statistically different. It is utilized as the statistical tool for hypothesis testing purposes in comparing fuel consumption differences between the two pavement types in each driving mode. Justification of a paired t-test can be illustrated as follow.

Suppose there are p_1 observations on street 1 on the jth day and

there are p_2 observations on street 2 on the jth day

The average of the p_1 observations is $\bar{x}_{1j}$, and

The average of the p_2 observations is $\bar{x}_{2j}$.

All observations are correlated, $j = 1, 2, \ldots, n$

The p_1 and p_2 observations can be put in a vector. This vector has a multivariate normal distribution.

$$\begin{bmatrix} \underset{\sim}{x}_{1j} \\ \underset{\sim}{x}_{2j} \end{bmatrix} \sim N\left(\begin{bmatrix} \mu_1 \underset{\sim}{1}_1 \\ \mu_2 \underset{\sim}{1}_2 \end{bmatrix}, \begin{bmatrix} \underset{\sim}{\Sigma}_{11} & \underset{\sim}{\Sigma}_{12} \\ \underset{\sim}{\Sigma}_{21} & \underset{\sim}{\Sigma}_{22} \end{bmatrix} \right) \quad ; j = 1, 2, \ldots, n$$

Where $\bar{x}_{1j}$ is a p_1 x 1 vector consisting of street 1 observations, and

$\bar{x}_{2j}$ is a p_2 x 1 vector consisting of street 2 observations.

$$\underset{\sim}{1}_1 = \begin{bmatrix} 1 \\ 1 \\ \vdots \\ 1 \end{bmatrix}_{(p_1 \times 1)} \quad , \quad \underset{\sim}{1}_2 = \begin{bmatrix} 1 \\ 1 \\ \vdots \\ 1 \end{bmatrix}_{(p_2 \times 1)}$$

Making a transformation by multiplying with the vector

$$\underset{\sim}{A} = \left[\frac{1}{p_1} \underset{\sim}{1}_1^{'}, \frac{-1}{p_2} \underset{\sim}{1}_2^{'} \right],\ 1 \times (p_1 + p_2)$$

Then,

$$\underset{\sim}{A} \begin{bmatrix} \underset{\sim}{x}_{1j} \\ \underset{\sim}{x}_{2j} \end{bmatrix} \sim N\left(\underset{\sim}{A} \begin{bmatrix} \mu_1 \underset{\sim}{1}_1 \\ \mu_2 \underset{\sim}{1}_2 \end{bmatrix}, \underset{\sim}{A} \begin{bmatrix} \underset{\sim}{\Sigma}_{11} & \underset{\sim}{\Sigma}_{12} \\ \underset{\sim}{\Sigma}_{21} & \underset{\sim}{\Sigma}_{22} \end{bmatrix} \underset{\sim}{A}' \right)$$

$$\underset{\sim}{A} \begin{bmatrix} \underset{\sim}{x}_{1j} \\ \underset{\sim}{x}_{2j} \end{bmatrix} = \left[\frac{1}{p_1} \underset{\sim}{1}_1^{'}, \frac{-1}{p_2} \underset{\sim}{1}_2^{'} \right] \begin{bmatrix} \underset{\sim}{x}_{1j} \\ \underset{\sim}{x}_{2j} \end{bmatrix} = \frac{1}{p_1} \underset{\sim}{1}_1^{'} \underset{\sim}{x}_{1j} - \frac{1}{p_2} \underset{\sim}{1}_1^{'} \underset{\sim}{x}_{2j}$$

$$\underset{\sim}{A} \begin{bmatrix} \underset{\sim}{x}_{1j} \\ \underset{\sim}{x}_{2j} \end{bmatrix} = \bar{x}_{1j} - \bar{x}_{2j}, \text{ a scalar}$$

$$\underset{\sim}{A} \begin{bmatrix} \mu_1 \underset{\sim}{1}_1 \\ \mu_2 \underset{\sim}{1}_2 \end{bmatrix} = \left[\frac{1}{p_1} \underset{\sim}{1}_1^{'}, \frac{-1}{p_2} \underset{\sim}{1}_2^{'} \right] \begin{bmatrix} \mu_1 \underset{\sim}{1}_1 \\ \mu_2 \underset{\sim}{1}_2 \end{bmatrix} = \frac{1}{p_1} \mu_1 \underset{\sim}{1}_1^{'} \underset{\sim}{1}_1 - \frac{1}{p_2} \mu_2 \underset{\sim}{1}_2^{'} \underset{\sim}{1}_2$$

$$\underset{\sim}{A} \begin{bmatrix} \mu_1 \underset{\sim}{1}_1 \\ \mu_2 \underset{\sim}{1}_2 \end{bmatrix} = \mu_1 - \mu_2$$

$$\underset{\sim}{A} \begin{bmatrix} \underset{\sim}{\Sigma}_{11} & \underset{\sim}{\Sigma}_{12} \\ \underset{\sim}{\Sigma}_{21} & \underset{\sim}{\Sigma}_{22} \end{bmatrix} \underset{\sim}{A}' = \sigma_D^2, \text{ a scalar}$$

The components in $\underset{\sim}{\Sigma}_{11}$, $\underset{\sim}{\Sigma}_{12}$, $\underset{\sim}{\Sigma}_{21}$, and $\underset{\sim}{\Sigma}_{22}$ are arbitrary.

Let $D_j = \bar{x}_{1j} - \bar{x}_{2j}; j = 1, 2, \ldots, n$

$$\mu_D = \mu_1 - \mu_2$$

Then $D_j \sim N(\mu_D, \sigma_D^2); j = 1, 2, \ldots, n$

Test $H_0 : \mu_1 = \mu_2$ is equivalent to test $H_0 : \mu_D = 0$.

Hence, this is a paired *t*-test.

Given μ_1 the average fuel consumption rates on a selected AC pavement and μ_2 the average fuel consumption rates on a selected PCC pavement, the hypotheses for the test would be:

H_0: $\mu_1 \leq \mu_2$

H_a: $\mu_1 > \mu_2$

4.2.1.1 The First Test Sites: Pecandale Drive (AC) vs. Abram Street (PCC)

The total fuel consumed was recorded and the corresponding consumption rates in gallons per mile were calculated. The resulting data under constant speed mode and acceleration mode were summarized in Table 4.1 and Table 4.2, respectively. The raw data associated with these tables are provided in Appendix C. Figure 4.3 also shows a comparison plot of fuel consumption between two pavement types under constant speed mode, while Figure 4.4 illustrates the comparison plot under acceleration mode.

Table 4.1 Average Fuel Consumption Rates for Pecandale Drive (AC) vs. Abram Street (PCC) under Constant Speed Mode

Date	Fuel Consumption (10^{-3} gpm)	
	AC	PCC
November 7, 2008	43.7	39.8
January 16, 2009	53.2	46.8
April 21, 2011	54.1	51.3
April 23, 2011	52.6	48.7
April 28, 2011	53.8	49.7
May 3, 2011	58.6	53.4
May 5, 2011	55.1	51.0

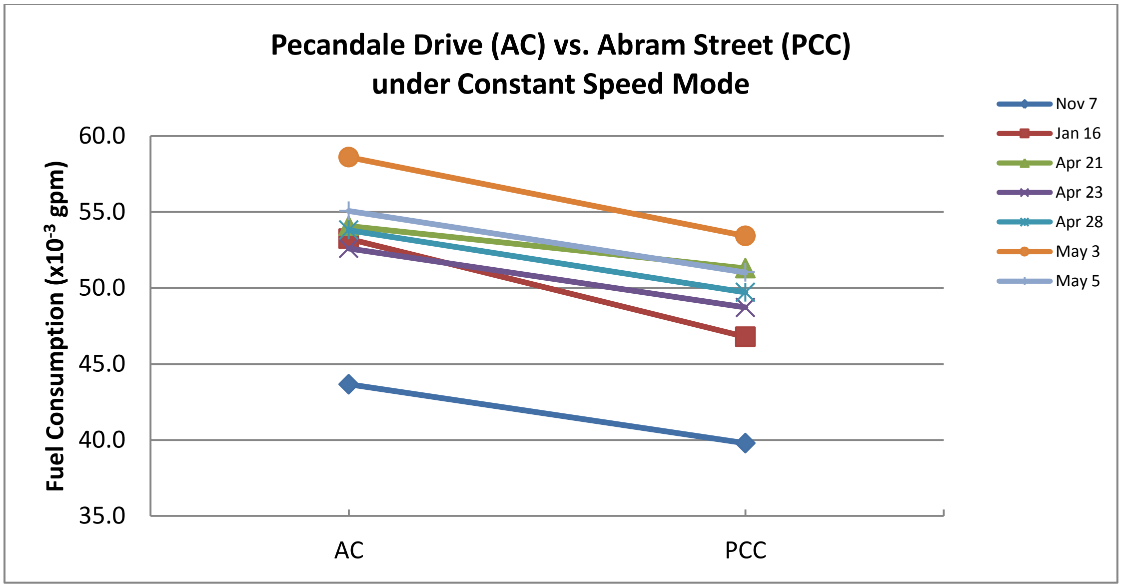


Figure 4.3 Comparison Plot for Pecandale Drive (AC) vs. Abram Street (PCC) under Constant Speed Mode

Table 4.2 Average Fuel Consumption Rates for Pecandale Drive (AC) vs. Abram Street (PCC) under Acceleration Mode

Date	Fuel Consumption (10^{-3} gpm)	
	AC	PCC
November 7, 2008	239.0	232.5
January 16, 2009	260.5	234.6
April 21, 2011	281.0	257.7
April 23, 2011	293.6	271.6
April 28, 2011	281.5	273.7
May 3, 2011	273.2	290.6
May 5, 2011	274.2	271.9

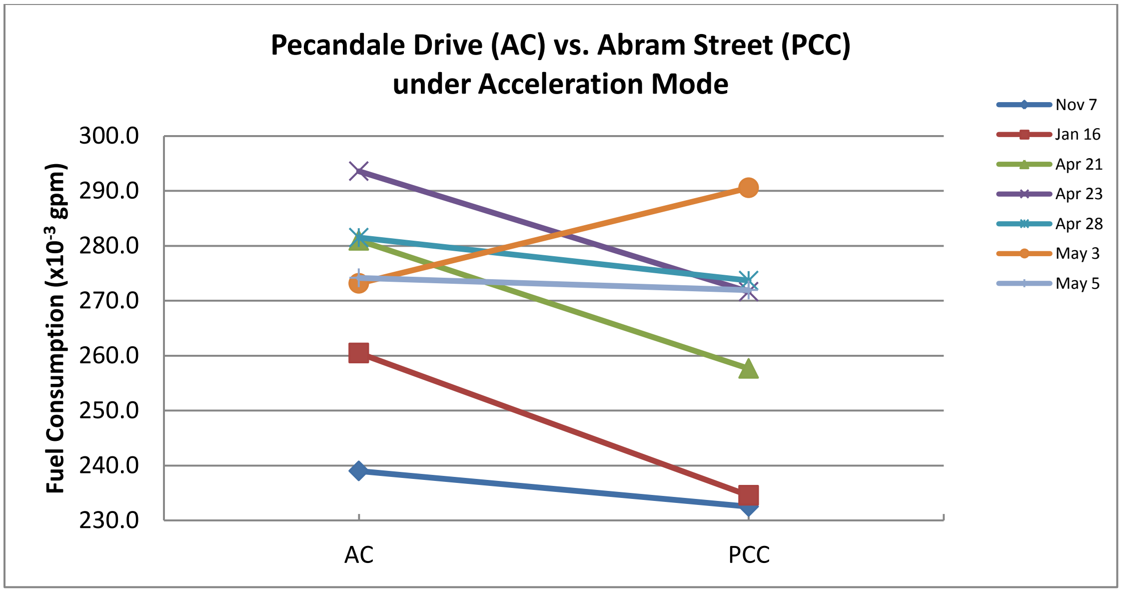


Figure 4.4 Comparison Plot for Pecandale Drive (AC) vs. Abram Street (PCC) under Acceleration Mode

Utilizing a paired t-test, it can be observed from the Pecandale Drive (AC) vs. Abram Street (PCC) that the calculated t-values based on fuel rate differences under all conditions were greater than their respective tabulated (critical) t-values (see Table 4.3). Consequently, all observed differences in fuel consumption rates were found to be statistically significant. At a constant speed of 30 mph, the PCC section was associated with lower consumption rate and the difference was statistically significant at a 10% level of significance. This was also the case for the acceleration mode.

Table 4.3 Hypothesis Test Results for Paired t-Test for Pecandale Drive (AC) vs. Abram Street (PCC) at 10% Level of Significance

Condition	t-statistics			
	DF	Calculated t	Tabulated t	Results
Constant Speed of 30 mph	6	9.8220	1.4398	significant
Acceleration of 3 mph/sec	6	1.7380	1.4398	significant

According to Figure 4.4, the fuel data collected on May 3rd under acceleration happened to have more fuel consumption rate on PCC section. This data could be an outlier as its trend was not consistent with the rest. However, when testing the hypothesis under acceleration mode by excluding this data, the null hypothesis was rejected, so the differences in fuel consumption rates were found to be statistically significant. Also, *p*-value was less than α, the result was statistically significant.

4.2.1.2 The Second Test Sites: Randol Mill Road (AC) vs. Road to Six Flags (PCC)

Fuel measurements were conducted on additional road sections, despite their different conditions from the first road sections, to investigate whether or not AC pavement has a higher vehicular fuel consumption rate than PCC pavement. Table 4.4 and Table 4.5 shows fuel consumption rates under constant speed mode and acceleration mode, respectively. The associated raw data are provided in Appendix C. The comparison plots of fuel consumption between Randol Mill Road (AC) and Road to Six Flags (PCC) under constant speed mode and acceleration mode were also depicted in Figure 4.5 and Figure 4.6 , respectively.

Table 4.4 Average Fuel Consumption Rates for Randol Mill Road (AC) vs. Road to Six Flags (PCC) under Constant Speed Mode

Date	Fuel Consumption (10^{-3} gpm)	
	AC	PCC
July 3, 2009	47.7	41.1
July 23, 2009	52.8	45.4
July 24, 2009	51.7	42.1
April 21, 2011	47.8	42.0
April 23, 2011	48.9	39.7
April 28, 2011	49.3	42.3
May 3, 2011	47.2	42.0

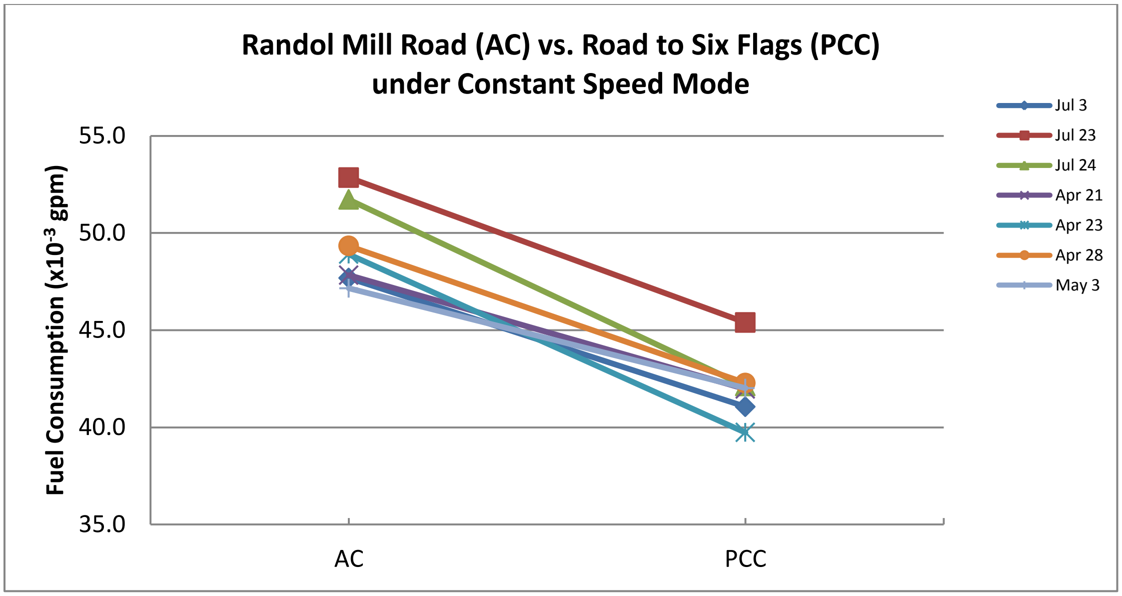


Figure 4.5 Comparison Plot for Randol Mill Road (AC) vs. Road to Six Flags (PCC) under Constant Speed Mode

Table 4.5 Average Fuel Consumption Rates for Randol Mill Road (AC) vs. Road to Six Flags (PCC) under Acceleration Mode

Date	Fuel Consumption (10^{-3} gpm)	
	AC	PCC
July 3, 2009	256.5	243.3
July 23, 2009	266.1	235.1
July 24, 2009	252.7	240.1
April 21, 2011	262.6	228.8
April 23, 2011	278.2	258.0
April 28, 2011	271.6	231.0
May 3, 2011	256.3	236.8

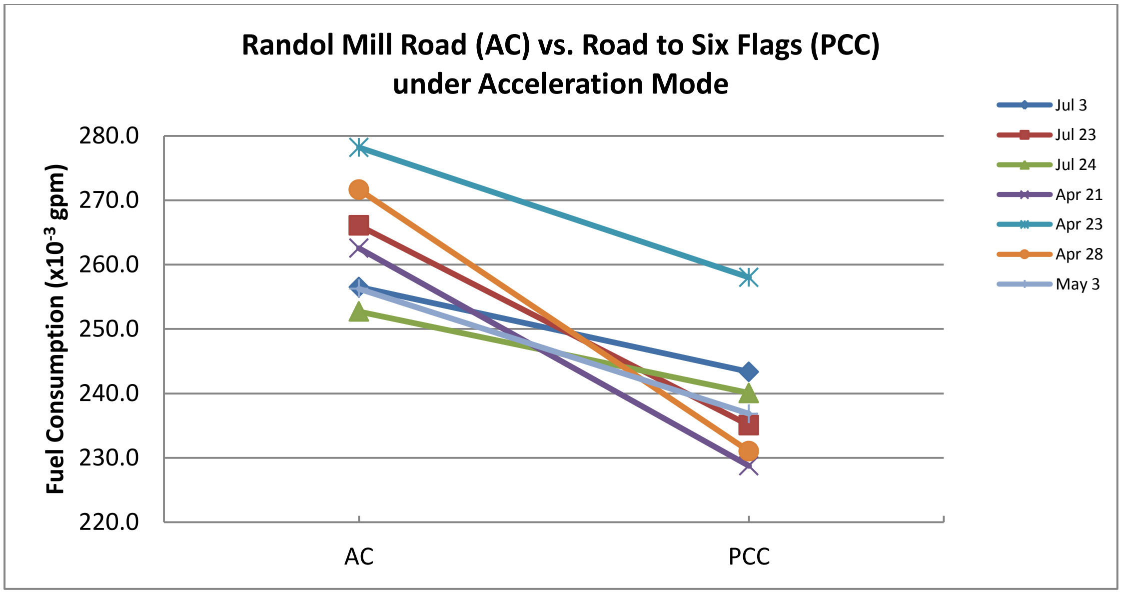


Figure 4.6 Comparison Plot for Randol Mill Road (AC) vs. Road to Six Flags (PCC) under Acceleration Mode

For these two road sections, the observed fuel consumption rates were tested for statistical significance at 10% level of significance. The fuel consumption rate for the PCC pavement was observed to be lower than the rate for the AC pavement in both driving modes. Table 4.6 summarizes the hypothesis test results.

Table 4.6 Hypothesis Test Results for Paired t-Test for Randol Mill Road (AC) vs. Road to Six Flags (PCC) at 10% Level of Significance

Condition	t-statistics			
	DF	Calculated t	Tabulated t	Results
Constant Speed of 30 mph	6	11.7505	1.4398	significant
Acceleration of 3 mph/sec	6	5.9723	1.4398	significant

4.2.2 p-Value

The *p*-value of a test is the smallest probability that would allow the null hypothesis to be rejected. The smaller the *p*-value, the more strongly the test rejects the null hypothesis. By comparing the *p*-value with selected value of α, the decision rule for testing H_0 against H_A can be written as reject H_0 if $p < \alpha$.

Table 4.7 and Table 4.8 present the test of *p*-value at 10% level of significance for the first test sites and the second test sites, respectively. On both test sites, it can be observed that the *p*-values under all conditions were smaller than the value of α equal to 0.10. As a result, all null hypotheses were rejected, the results were statistically significant. This supports the results from the previous paired t-test on both test sites. At a constant speed of 30 mph, the PCC sections were associated with a lower consumption rate and the differences were statistically significant at a 10% level of significance. Under the acceleration mode at a 0.10 level, the differences were also statistically significant with the PCC sections having lower fuel rates. It can be further observed from Table 4.7 and Table 4.8 that if the significance level is 0.05, the fuel consumption rates for the PCC pavements would be lower than the rates for the AC pavements at a constant speed mode. However, it is not the case for the acceleration mode on Pecandale Drive and Abram Street, because the differences are not statistically significant.

Table 4.7 Test of *p*-Value for Pecandale Drive (AC) vs. Abram Street (PCC) at 10% Level of Significance

Condition	*p*-value test at α=0.10	
	p-value	Results
Constant Speed of 30 mph	0.000032	significant
Acceleration of 3 mph/sec	0.066441	significant

Table 4.8 Test of *p*-Value for Randol Mill Road (AC) vs. Road to Six Flags (PCC) at 10% Level of Significance

Condition	*p*-value test at α=0.10	
	p-value	Results
Constant Speed of 30 mph	0.000011	significant
Acceleration of 3 mph/sec	0.000494	significant

The study further investigated the hypothesis tests in the case that all observed data were merged for each driving mode. For asphalt sections, fuel consumption data from Pecandale Drive were combined with data from Randol Mill Road, whereas for concrete sections fuel data from Abram Street were combined with data from Road to Six Flags. Those were based on the same driving conditions. That is, paired t-tests were carried out for AC vs. PCC sections under constant speed and acceleration modes.

Table 4.9 summarizes the hypothesis test results. It can be observed that the calculated t-values based on fuel rate differences under both driving conditions were higher than their tabulated t-values. Thus, all differences in fuel consumption rates were found to be statistically significant at a 10% level of significance with the fuel consumption rates on AC sections being higher. *p*-values (see Table 4.10) also resulted that all differences were significant as *p*-values were less than α, thereby null hypothesis rejected.

Table 4.9 Hypothesis Test Results for Paired t-Test for AC vs. PCC Pavements at 10% Level of Significance

Condition	t-statistics			
	DF	Calculated t	Tabulated t	Results
Constant Speed of 30 mph	13	10.5966	1.3502	significant
Acceleration of 3 mph/sec	13	4.3713	1.3502	significant

Table 4.10 Test of *p*-Value for AC vs. PCC Pavements at 10% Level of Significance

Condition	*p*-value test at α=0.10	
	p-value	Results
Constant Speed of 30 mph	0.00000008	significant
Acceleration of 3 mph/sec	0.0003783	significant

To reconsider the standard deviations (σ) and sample size (n) after all fuel measurement data were observed, Table 4.11 was generated as shown.

Table 4.11 Standard Deviations and Sample Size after All Data Observed

	Pecandale (AC) vs. Abram (PCC)		Randol Mill (AC) vs. Six Flags (PCC)	
	Constant Speed	Acceleration	Constant Speed	Acceleration
α	0.10	0.10	0.10	0.10
$1-\beta$	0.90	0.90	0.90	0.90
r	2	2	2	2
σ (x10^{-3} gpm)	4.9	19.6	4.2	15.6
max (x10^{-3} gpm)	58.6	293.6	52.8	278.2
min (x10^{-3} gpm)	39.8	232.5	39.7	228.8
Δ (x10^{-3} gpm)	10.0	25.0	10.0	25.0
n	6	12	5	9

The standard deviations at constant speed mode on both pair of test sites (4.9 and 4.2 x10^{-3} gpm) were smaller than those used in determining sample size process (see

3.4.2), while the standard deviations under acceleration mode (19.6 and 15.6 x10^{-3} gpm) were greater than those used in determining the sample size. Then, the new sample sizes for each scenario were retrieved by using Table 3.6. The new sample sizes on both pair of sections at constant speed were smaller than those calculated from the preliminary study. The first test sites have 6 sample sizes, compared to previous sample sizes of 7, while the second test sites have 5 sample sizes, compared to previous sample sizes of 7. On the other hand, the new sample sizes under acceleration were larger than those from the preliminary study. The new sample sizes of the first and second test sites are 12 and 9, respectively. The sample sizes under acceleration from preliminary study are 7 and 6 for the first and second test sites, respectively.

4.3 Estimation of Fuel Consumption and CO_2 Emissions including Cost Differences

4.3.1 Estimation of Fuel Consumption and CO_2 Emissions

This section is to quantify the fuel consumed by the test vehicle over two pavement types as a basis for projecting potential costs or savings of one pavement type versus another over a project design life. Fuel consumption rates are used to project fuel consumption rate differences for other vehicles in the traffic mix using linear projections based on respective vehicle weight ratios. The amounts of fuel consumption are also used to estimate CO_2 emissions.

The average fuel consumption rates are used as the basis for development of the afore-mentioned spreadsheet tool (Chang et al., 1976; Wood et al., 1981). As discussed earlier, under both driving modes, the fuel consumption rates for the PCC pavement was found to be statistically (at $\alpha = 10\%$) lower than the corresponding rates for the AC pavement. To illustrate the cumulative effect of these differences, the fuel rates for the constant speed condition were applied to the annual vehicle miles of travel (VMT) in the Dallas-Fort Worth (DFW) region of Texas. In 2007, for example, the total annual VMT in the nine-county DFW region was estimated to be 62,697 million miles (North Central Texas Council of Government, 2007). The fuel consumption rates used are the average of 7-day fuel rates on Randol Mill and Road to Six Flags as Road to Six Flags could be a representative of JPCP, the most common type of concrete pavement. It is the most commonly used type of concrete pavement in the U.S since about 43 states use or have JPCP design procedures (Delatte, 2008; Washington State Department of Transportation, 2003). The fuel rates then were applied to the VMT to obtain the total annual fuel consumption estimates for a hypothetical mix of vehicles, as shown in Table 4.12 (for AC) and Table 4.13 (for PCC).

Table 4.12 Calculations of Annual Fuel Consumption for the Dallas-Fort Worth Region of Texas under AC Pavement and Constant Speed Mode

Vehicle Type	Average Vehicle Weight (lbs)	VMT (million miles/yr)	% in the Mix	Fuel Rate (gals/mi)	Fuel Consumed (million gals/yr)
LDGV	3,000	42,273	67.425	0.0198	835.3
LDGT1	4,000	2,708	4.318	0.0263	71.3
LDGT2	4,000	9,013	14.376	0.0263	237.5
LDGT3	7,500	2,605	4.155	0.0494*	128.7
LDGT4	7,500	1,198	1.911	0.0494	59.2
HDGV2B	9,500	494	0.788	0.0626	30.9
HDGV3	12,000	141	0.225	0.0790	11.1
HDGV4	15,000	73	0.116	0.0988	7.2
HDGV5	18,000	40	0.063	0.1186	4.7
HDGV6	23,000	66	0.106	0.1515	10.1
HDGV7	29,500	16	0.026	0.1943	3.2
HDGV8A	47,000	16	0.025	0.3096	4.9
HDGV8B	80,000	2	0.003	0.5269	1.1
LDDV	3,000	42	0.068	0.0198	0.8
LDDT12	4,000	10	0.016	0.0263	0.3
HDDV2B	9,500	574	0.915	0.0626	35.9
HDDV3	12,000	163	0.259	0.0790	12.9
HDDV4	15,000	119	0.190	0.0988	11.8
HDDV5	18,000	80	0.128	0.1186	9.5
HDDV6	23,000	259	0.412	0.1515	39.2
HDDV7	29,500	92	0.147	0.1943	17.9
HDDV8A	47,000	155	0.247	0.3096	48.0
HDDV8B	80,000	2,075	3.310	0.5269	1,093.5
MC	700	46	0.074	0.0046	0.2
HDGB	15,000	14	0.022	0.0988	1.4
HDDBT	35,000	49	0.078	0.2305	11.2
HDDBS	22,500	80	0.128	0.1482	11.9
LDDT34	7,500	292	0.466	0.0494	14.4
	∑	62,697	100		**2,714.1**

* Measured in the field

Table 4.13 Calculations of Annual Fuel Consumption for the Dallas-Fort Worth Region of Texas under PCC Pavement and Constant Speed Mode

Vehicle Type	Average Vehicle Weight (lbs)	VMT (million miles/yr)	% in the Mix	Fuel Rate (gals/mi)	Fuel Consumed (million gals/yr)
LDGV	3,000	42,273	67.425	0.0168	711.9
LDGT1	4,000	2,708	4.318	0.0225	60.8
LDGT2	4,000	9,013	14.376	0.0225	202.4
LDGT3	7,500	2,605	4.155	0.0421*	109.7
LDGT4	7,500	1,198	1.911	0.0421	50.4
HDGV2B	9,500	494	0.788	0.0533	26.4
HDGV3	12,000	141	0.225	0.0674	9.5
HDGV4	15,000	73	0.116	0.0842	6.1
HDGV5	18,000	40	0.063	0.1010	4.0
HDGV6	23,000	66	0.106	0.1291	8.6
HDGV7	29,500	16	0.026	0.1656	2.7
HDGV8A	47,000	16	0.025	0.2638	4.2
HDGV8B	80,000	2	0.003	0.4491	1.0
LDDV	3,000	42	0.068	0.0168	0.7
LDDT12	4,000	10	0.016	0.0225	0.2
HDDV2B	9,500	574	0.915	0.0533	30.6
HDDV3	12,000	163	0.259	0.0674	11.0
HDDV4	15,000	119	0.190	0.0842	10.0
HDDV5	18,000	80	0.128	0.1010	8.1
HDDV6	23,000	259	0.412	0.1291	33.4
HDDV7	29,500	92	0.147	0.1656	15.2
HDDV8A	47,000	155	0.247	0.2638	40.9
HDDV8B	80,000	2,075	3.310	0.4491	931.9
MC	700	46	0.074	0.0039	0.2
HDGB	15,000	14	0.022	0.0842	1.2
HDDBT	35,000	49	0.078	0.1965	9.6
HDDBS	22,500	80	0.128	0.1263	10.2
LDDT34	7,500	292	0.466	0.0421	12.3
	∑	62,697	100		**2,313.1**

* Measured in the field

The field-measured fuel rates under the constant speed mode in Table 4.12 and Table 4.13 correspond to the instrumented van, LDGT3 (7,500-lb weight). For the purpose of calculations summarized in these tables, fuel consumption rates for all other vehicle classes were estimated from the field-measured rate based on the weight ratio of the two respective classes. For example, a 15,000-lb vehicle was estimated to have twice as large a fuel consumption rate than the 7,500-lb test vehicle. As mentioned earlier, this method of approximating fuel consumption rates was based on a number of fuel consumption studies that have shown fuel consumption ratios to be approximately proportional to vehicle weight ratios (Chang et al., 1976; Wood et al., 1981). The total fuel consumption amounts per annum then were estimated using those rates and the total VMT for each vehicle class. They resulted in an annual fuel consumption of 2,714 million gallons for AC pavement and 2,313 million gallons for PCC pavement.

The CO_2 emissions from mobile sources may be calculated using emission fact provided by EPA's Office of Transportation and Air Quality (OTAQ). A gallon of conventional gasoline generates 19.4 pounds (8.8 kg) of CO_2 emissions (U.S. Environmental Protection Agency, 2005). Therefore, the CO_2 emissions per annum on AC pavement is estimated to be 23.88 million metric tons, while CO_2 emissions estimation on PCC pavement is 20.36 million metric tons, summarized in Table 4.14. It is noted that these estimates assume all the VMT occurs at a 30-mph constant speed.

Table 4.14 Total Annual CO_2 Emissions for the Dallas-Fort Worth Region of Texas under Constant Speed

	Fuel Consumed (million gals/yr)	Total CO_2 (million metric tons/yr)
AC, Constant Speed (30 mph)	2,714	**23.88**
PCC, Constant Speed (30 mph)	2,313	**20.35**

The fuel consumption weight proportionality is a feasible approach for this research study when there is no actual fuel consumption rates of all vehicle classes provided. In lieu of testing on every vehicle class, the fuel consumption data were made by the vehicle available at the time. The fuel consumption weight proportionality assumption is reasonable to apply as weight resists movement. The more the vehicle weight is, the more the energy is required by the engine to accelerate the vehicle and to overcome rolling resistance. However, it should be noted that this method was experimented under urban traffic condition at low speeds where weight and traffic conditions have a direct impact on the fuel vehicle consumed (Wood et al., 1981). Therefore, this approach could be a conservative assumption as numbers of acceleration and deceleration, and stop-and-go can cause high fuel consumption rate. Using this method for highway driving is doable to compare fuel consumption of vehicles that have similar frontal areas. Because, in addition to vehicle weight, aerodynamic drag is a big issue for a large frontal-area vehicle driving at highway speeds. A larger frontal area creates higher drag force that acts on a moving vehicle.

4.3.2 Estimation of Fuel Saving and Emissions Reductions

As the overall results for the constant speed mode are summarized in Table 4.14, if the annual vehicle miles of travel in the DFW region took place at a constant speed of 30 mph all on PCC pavements similar to the ones in the test sections, the statistically lower fuel rate could result in an annual fuel savings of about 401 million gallons and an annual CO_2 reduction of about 3.53 million metric tons. Assuming an average gasoline price of about \$3.29 a gallon and an average CO_2 clean-up cost of about \$18 per metric tons (EcoBusinessLinks, 2009), these differences (see Table 4.15) would amount to a savings of about \$1.38 billion per year in the DFW region, a cost savings which should be considered in the life-cycle cost analysis of alternative city street pavement projects.

Table 4.15 Annual Fuel Savings and Emissions Reductions in Favor of PCC Pavement for the Dallas-Fort Worth Region of Texas under Constant Speed

	(million/yr)
Fuel Savings	\$1,319
Emissions Reductions	\$64
Total Savings	**\$1,383**

4.3.3 Estimation of CO_2 Emissions of a Mile Section of a Typical City Street

Estimating CO_2 emissions of a pavement involves many variable inputs. The examples are carbon footprint from the material production, pavement construction, and maintenance process of the pavement itself and carbon footprint produced by the vehicles using that pavement section.

Abram Street is chosen for analysis as a typical city street. Abram Street has an average daily traffic (ADT), which represents an estimate of the number of vehicles traveling along this section of Abram Street, of 12,003 vehicles per day (City of Arlington, 2011).

Table 4.16 presents fuel consumption on a one-mile long section of Abram Street. The average fuel consumption rate on this section driven by the instrumented van is 0.0487 gpm. The fuel rate was projected to the other vehicle types in the mix by vehicle weight ratio. The ADT was calculated based on % of vehicle mix. The fuel rates then were multiplied to the ADT to obtain the total fuel consumption estimates for a mix of vehicles. As a result, the total fuel consumed per day on a one-mile PCC section under constant speed is estimated to be 512 gallons.

The same steps were applied to a one-mile AC section. AC section has an average fuel consumption rate of 0.0530 gpm, from Pecandale Drive, but for comparison, the study assumed that this section has the same ADT as PCC section. Table 4.17 show the fuel consumption amounts per one mile per day in a hypothetical mix of vehicles, which yielding to 558 gallons.

Table 4.16 Calculations of Daily Fuel Consumption on a One-Mile PCC Section of a Typical City Street under Constant Speed Mode

Vehicle Type	Average Vehicle Weight (lbs)	% in the Mix	ADT (vpd)	Fuel Rate (gals/mi)	Fuel Consumed (gals/mile/day)
LDGV	3,000	67.425	8,093	0.0195	157.7
LDGT1	4,000	4.318	518	0.0260	13.5
LDGT2	4,000	14.376	1,726	0.0260	44.8
LDGT3	7,500	4.155	499	**0.0487**	24.3
LDGT4	7,500	1.911	229	0.0487	11.2
HDGV2B	9,500	0.788	95	0.0617	5.8
HDGV3	12,000	0.225	27	0.0779	2.1
HDGV4	15,000	0.116	14	0.0974	1.4
HDGV5	18,000	0.063	8	0.1169	0.9
HDGV6	23,000	0.106	13	0.1493	1.9
HDGV7	29,500	0.026	3	0.1916	0.6
HDGV8A	47,000	0.025	3	0.3052	0.9
HDGV8B	80,000	0.003	0	0.5195	0.2
LDDV	3,000	0.068	8	0.0195	0.2
LDDT12	4,000	0.016	2	0.0260	0.1
HDDV2B	9,500	0.915	110	0.0617	6.8
HDDV3	12,000	0.259	31	0.0779	2.4
HDDV4	15,000	0.190	23	0.0974	2.2
HDDV5	18,000	0.128	15	0.1169	1.8
HDDV6	23,000	0.412	49	0.1493	7.4
HDDV7	29,500	0.147	18	0.1916	3.4
HDDV8A	47,000	0.247	30	0.3052	9.1
HDDV8B	80,000	3.310	397	0.5195	206.4
MC	700	0.074	9	0.0045	0.0
HDGB	15,000	0.022	3	0.0974	0.3
HDDBT	35,000	0.078	9	0.2273	2.1
HDDBS	22,500	0.128	15	0.1461	2.3
LDDT34	7,500	0.466	56	0.0487	2.7
	∑	100	12,003		**512.2**

* Measured in the field

Table 4.17 Calculations of Daily Fuel Consumption on a One-Mile AC Section of a Typical City Street under Constant Speed Mode

Vehicle Type	Average Vehicle Weight (lbs)	% in the Mix	ADT (vpd)	Fuel Rate (gals/mi)	Fuel Consumed (gals/mile/day)
LDGV	3,000	67.425	8,093	0.0212	171.6
LDGT1	4,000	4.318	518	0.0283	14.7
LDGT2	4,000	14.376	1,726	0.0283	48.8
LDGT3	7,500	4.155	499	**0.0530**	26.4
LDGT4	7,500	1.911	229	0.0530	12.2
HDGV2B	9,500	0.788	95	0.0671	6.4
HDGV3	12,000	0.225	27	0.0848	2.3
HDGV4	15,000	0.116	14	0.1060	1.5
HDGV5	18,000	0.063	8	0.1272	1.0
HDGV6	23,000	0.106	13	0.1625	2.1
HDGV7	29,500	0.026	3	0.2085	0.7
HDGV8A	47,000	0.025	3	0.3321	1.0
HDGV8B	80,000	0.003	0	0.5653	0.2
LDDV	3,000	0.068	8	0.0212	0.2
LDDT12	4,000	0.016	2	0.0283	0.1
HDDV2B	9,500	0.915	110	0.0671	7.4
HDDV3	12,000	0.259	31	0.0848	2.6
HDDV4	15,000	0.190	23	0.1060	2.4
HDDV5	18,000	0.128	15	0.1272	1.9
HDDV6	23,000	0.412	49	0.1625	8.0
HDDV7	29,500	0.147	18	0.2085	3.7
HDDV8A	47,000	0.247	30	0.3321	9.9
HDDV8B	80,000	3.310	397	0.5653	224.6
MC	700	0.074	9	0.0049	0.0
HDGB	15,000	0.022	3	0.1060	0.3
HDDBT	35,000	0.078	9	0.2473	2.3
HDDBS	22,500	0.128	15	0.1590	2.4
LDDT34	7,500	0.466	56	0.0530	3.0
	∑	100	12,003		**557.5**

* Measured in the field

According to Nair and Bhat (2000), many metropolitan planning organizations (MPOs) typically calculate the VMT on city streets as about 10% of the VMT on all other streets. A fraction of 0.10 of the total VMT in DFW nine-county region is on city streets and is then multiplied to the fuel consumption in the region. Therefore, the amounts of fuel consumed per day on a one-mile section of AC vs. PCC were about 55.8 and 51.2 gallons, respectively. As a gallon of conventional gasoline produces 19.4 pounds (8.8 kg) of CO_2 emissions, the CO_2 emissions on AC are estimated to be 0.491 metric tons, while CO_2 emissions estimation on PCC pavement is 0.450 metric tons. Table 4.18 presents this study's estimate of the carbon footprint released by the mix of vehicles under 30-mph constant speed on a one-mile long AC and PCC city streets per day.

Table 4.18 Daily CO_2 Emissions on a One-Mile Section of a Typical City Street under Constant Speed Mode

	Fuel Consumed (gals/mi/day)	Total CO_2 (metric tons/mi/day)
AC, Constant Speed (30 mph)	55.75	**0.491**
PCC, Constant Speed (30 mph)	51.22	**0.450**

As mentioned earlier that a Canadian study (Brown, 2009) compares two typical residential pavement cross-sections, an AC and a PCC pavement section in southern Ontario. The study estimates the contributions of these two pavement materials to the carbon footprint of a one-kilometer long section. The calculation is based on the CO_2

released during the material production, pavement construction and maintenance phase of the project.

Carbon footprint released per day is summarized in Table 4.19. After unit conversion of pavement length, the Canadian study presents that under production, construction, and maintenance phase, the AC section is 53% of the CO_2 emissions from PCC section. The analysis from ADT on city pavement section shows small differences of CO_2 emissions of AC over PCC section. It can be seen that the carbon footprint from fuel difference does dwarf the carbon footprint released from the material production, pavement construction, and maintenance phases. The traffic calculation in this study was estimated based on average daily traffic which does not count the distance traveled element. If distance traveled is taken into account, it could represent a more difference in fuel consumed and also the carbon footprint over a city area.

Table 4.19 Daily CO_2 Emissions on a One-Mile AC vs. PCC Sections of a Typical City Street under 30-mph Constant Speed from Pavement Production, Construction, Maintenance, and Traffic

	CO_2 Emissions (metric tons/mi/day)	
	AC	PCC
Production, Construction, and Maintenance	0.019	0.036
Traffic	0.491	0.450
Total	**0.510**	**0.486**

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The goal of this study was to investigate any statistically significant differences which might exist in fuel consumption rates on typical concrete versus asphalt city streets. The study was conducted through field data collections using an instrumented van.

It was observed that under urban driving speeds of 30 mph, the fuel consumption per unit distance is lower on concrete pavements compared to asphalt pavements. These findings were based on test runs on two sets of typical Portland Cement Concrete and Asphalt Concrete street sections in Arlington, Texas, with each pair of study sites having similar gradient and roughness index values. All observed differences were found to be statistically significant at a 10% level of significance.

The annual potential costs or savings in fuel consumed and CO_2 emissions generated were shown to be substantial over the Dallas-Fort Worth region. As a result, it is recommended that these costs or savings be considered in the life cycle cost analysis of alternative projects. Differences in CO_2 emissions should also be considered in life cycle analysis when estimating the carbon footprint of particular pavement materials to be used.

Estimation of carbon footprint is an important step in assessing the sustainability of city development projects and the overall life cycle analysis of projects. In pavement projects, specifically, the focus has been on estimating the carbon footprint of the production cycle of various pavement materials as well as the initial construction phase. A key finding of this study is that any such sustainability assessment must also consider the emissions differences based on operations of motor vehicles on various pavement surfaces. When considering a 20-50 year design life that is typical for city streets and the annual vehicle miles of travel, such differences could help dwarf carbon footprint estimations from the material production or pavement construction phases.

5.2 Recommendations

Critics of this study might argue that the numbers presented herein are not accurate estimates of the actual costs and savings realized in the Dallas-Fort Worth or any other urban region. This is because the examples presented are based on the mixes of vehicles, all driven at a constant speed of 30 mph. Furthermore, the fuel consumption rates per unit distance are developed based on a fairly limited sample of population of asphalt and concrete pavement types and typical pavement cross-sections in a city. Indeed it can be argued that to have accurate numbers, a more comprehensive study must be conducted, which includes the variety of asphalt and concrete mix designs used in city pavements as well as a broader sample of cross-section thicknesses of crown layers and base materials. Such a study should also include direct fuel rate measurements for a variety of vehicle types driven under a range of drive cycles as opposed to extrapolating the fuel consumption characteristics of one vehicle driven at a constant speed to other vehicle types and speed regimes. Thirdly, to better control exogenous factors such as wind speed and direction, temperature, and humidity perhaps the tests should be conducted using pavement sections constructed indoors where the ambient environment is controlled. In addition to IRI values, direct measurements of the skid resistance would be needed for each pavement section being tested. Last but not least, the measurements should be made under a much wider range of ambient humidity and temperatures than typically experienced in the Dallas-Fort Worth region.

Of course, if all these factors are to be considered it could be possible to show beyond doubt that one type of pavement results in better fuel efficiency than another and by how much. This would also substantially improve the accuracy of estimates of user costs and savings. But it is important to note that the numerical examples in this research are intended to illustrate how significant minute differences in fuel consumption and emissions could be over the design life of a project. However, these results are at best applicable to the specific pavement types studied and the test vehicle used. In fact, it would not be feasible to develop, based on these specific results, very accurate estimation algorithms that cover the entire spectrum of vehicle classes and pavement mix designs and cross-sections.

In accounting for user costs or savings for specific design alternatives, a more sensible approach could be to conduct similar tests of differences in fuel consumption rates over pavement sections already constructed to the intended specifications and using a representative vehicle with the highest proportion in the vehicle mix. In this vein, the study results presented used a typical minivan driven over typical HMA and PCC pavement cross-sections in the study region to illustrate that there could be statistically significant differences in fuel consumption and emissions for one pavement type versus another. Furthermore, numerical examples showed that such differences, while small on a per mile basis, could be very large over the design life of a project and should therefore be considered in any life cycle cost analysis or life cycle analysis of carbon footprints of alternative pavement designs.

APPENDIX A

INTERNATIONAL ROUGHNESS INDEX MEASUREMENTS

```
Ride Quality Analysis  Rel 2008.11.11
TxDOT Smoothness Specification  5880  Pay Schedule 3
Report run on  Friday  Feb 27 2009  3:03:50PM
Input profile data file created  Friday  Feb 27 2009  10:25:48AM

District  2                                     Highway  PECANDALE_DR
Area Office  FT worth                           Beg RM  0000 +00.000
County  220                                     Beg Station  0000+00.0
CSJ  JEFF HOWDES                                Lane roadbed  K1
Phone  FM2122E                                  Name
Input       file             t:\dalpme\uta          project       with
profiler\cty220_pecandale_st_20090227_1624.pro
*** eastbound outside lane
*** Beg Station 0000+00.0

No Bump penalties assessed.
Bonus paid for average IRIs of  30($600) to 60($0)
No penalties assessed for high IRIs.
Bonus NOT paid in sections with bump.

Profile Length(Miles)  0.3612  Length(Station Units)  0019+07.1ft.

Distance   Station           Type  Width(feet)    Elev(inches)
00.0009    0000+04.5         Bump        .7         .19
00.0019    0000+09.8         Dip        4.0        -.25
00.0033    0000+17.6         Bump       2.2         .18
00.0039    0000+20.3         Bump       1.3         .17
00.0050    0000+26.5         Dip        3.4        -.23
00.0074    0000+39.2         Dip         .5        -.16
00.0076    0000+39.9         Dip         .2        -.15
00.0078    0000+41.2         Dip         .2        -.15
00.0079    0000+41.7         Dip        4.0        -.22
00.0112    0000+59.2         Bump       4.7         .25
00.0138    0000+72.8         Dip        4.2        -.24
00.0167    0000+88.0         Bump       7.4         .22
00.0188    0000+99.5         Dip        8.3        -.30
00.0321    0001+69.7         Bump       3.1         .17
00.0350    0001+84.8         Dip         .4        -.16
00.0489    0002+58.3         Bump        .2         .15
00.0490    0002+58.6         Bump       1.6         .18
00.0506    0002+67.3         Dip        3.6        -.20
00.0603    0003+18.4         Dip         .2        -.15
00.0604    0003+18.7         Dip         .7        -.17
00.0942    0004+97.1         Bump        .5         .16
00.0957    0005+05.1         Dip        5.4        -.25
00.1192    0006+29.4         Dip        2.9        -.23
00.1643    0008+67.8         Dip        4.2        -.27
00.1672    0008+82.8         Bump       2.0         .19
00.1703    0008+99.0         Dip        2.9        -.17
00.1922    0010+14.6         Bump        .2         .15
00.1923    0010+15.5         Bump        .2         .15
00.1932    0010+20.2         Dip        5.1        -.44
00.1954    0010+31.6         Bump        .7         .18
00.1956    0010+32.6         Bump       2.4         .21
00.2027    0010+70.3         Bump        .2         .16
00.2028    0010+71.0         Bump       1.3         .18
00.2034    0010+73.8         Bump        .4         .16
00.2533    0013+37.7         Dip         .9        -.16
00.2541    0013+41.5         Dip         .9        -.18
```

```
Distance   Station          Type  Width(feet)    Elev(inches)
00.2550    0013+46.5        Dip      3.3         -.20
00.2577    0013+60.9        Bump     7.1          .27
00.2592    0013+68.3        Bump     4.0          .21
00.2608    0013+77.2        Dip      6.7         -.51
00.2626    0013+86.7        Bump     2.7          .20
00.2642    0013+95.2        Bump     2.9          .22
00.2795    0014+75.6        Bump     2.9          .22
00.2810    0014+83.8        Dip       .2         -.15
00.2812    0014+84.5        Dip       .4         -.15
00.2915    0015+39.3        Dip       .2         -.15
00.2916    0015+39.8        Dip       .5         -.17
00.3080    0016+26.4        Dip       .7         -.18
00.3093    0016+33.0        Bump     8.3          .20
00.3160    0016+68.3        Dip      1.1         -.16
00.3564    0018+81.8        Dip       .2         -.17
00.3565    0018+82.2        Dip       .2         -.15
00.3565    0018+82.5        Dip      4.4         -.22
00.3583    0018+91.6        Bump     1.6          .17
00.3586    0018+93.6        Bump      .5          .16
00.3588    0018+94.5        Bump      .5          .16
Bumps/dips detected   56

Distance Station PSI   IRI(L)  IRI(R)  Avg IRI  Pay*SectLen        Pay
00.1000  5+28.0  2.33  153.45  230.29  192.00  $  0*(0.1000/0.10)   $0
00.2000  10+56.0 2.53  114.39  237.37  176.00  $  0*(0.1000/0.10)   $0
00.3000  15+84.0 2.55  120.08  227.13  174.00  $  0*(0.1000/0.10)   $0
00.3612  19+07.1 2.46  125.35  236.88  181.00  $  0*(0.0612/0.10)   $0
                                           Pay Adjustment Subtotal   $0
Ave Left IRI  128.6   Ave Right IRI  232.5  Ave IRI  180.55
Total IRI adjustments   $     0
Total Bump adjustments  $     0
Total adjustments       $     0
```

```
Ride Quality Analysis  Rel 2008.11.11
TxDOT Smoothness Specification  5880  Pay Schedule 3
Report run on  Friday  Feb 27 2009  2:59:30PM
Input profile data file created  Friday  Feb 27 2009  10:30:14AM

District  2                                     Highway  ABRAM_ST
Area Office  Ft worth                           Beg RM  0000 +00.000
County  220                                     Beg Station  0000+00.0
CSJ  JEFF HOWDES                                Lane roadbed  K1
Phone  FM2122E                                  Name
Input       file              t:\dalpme\uta       project       with
profiler\cty220_abram_st_20090227_1628.pro
*** eastbound outside lane
*** Beg Station 0000+00.0

No Bump penalties assessed.
Bonus paid for average IRIs of  30($600) to 60($0)
No penalties assessed for high IRIs.
Bonus NOT paid in sections with bump.

Profile Length(Miles)  0.7276  Length(Station Units)  0038+41.7ft.

Distance   Station          Type  Width(feet)    Elev(inches)
00.0129    0000+68.1        Dip         .5       -.17
00.0132    0000+69.9        Dip         .4       -.16
00.0262    0001+38.5        Dip        2.5       -.17
00.0382    0002+01.8        Bump        .2        .15
00.0670    0003+53.9        Bump        .2        .15
00.0993    0005+24.5        Bump       2.0        .20
00.0998    0005+26.7        Bump       2.5        .20
00.1003    0005+29.4        Bump        .4        .16
00.1051    0005+54.8        Bump        .2        .15
00.1052    0005+55.4        Bump       1.3        .20
00.1313    0006+93.5        Dip        2.9       -.23
00.1457    0007+69.2        Dip         .4       -.16
00.1461    0007+71.2        Dip         .4       -.15
00.2070    0010+93.2        Dip        4.2       -.25
00.2079    0010+97.5        Dip         .2       -.15
00.2080    0010+98.1        Dip         .4       -.16
00.2081    0010+98.8        Dip         .9       -.17
00.2094    0011+05.7        Bump        .2        .15
00.2095    0011+06.1        Bump       2.2        .18
00.2102    0011+09.7        Bump        .2        .15
00.2391    0012+62.5        Dip        5.8       -.28
00.2416    0012+75.6        Bump       2.4        .19
00.2615    0013+80.7        Bump        .2        .15
00.2873    0015+17.2        Dip         .9       -.17
00.2875    0015+18.2        Dip         .4       -.16
00.2877    0015+19.0        Dip         .5       -.16
00.2878    0015+19.7        Dip         .4       -.16
00.2906    0015+34.2        Bump        .2        .16
00.2907    0015+34.8        Bump        .4        .15
00.3441    0018+16.6        Bump        .2        .15
00.3443    0018+17.7        Bump       2.5        .20
00.3451    0018+22.1        Bump        .2        .15
00.3474    0018+34.2        Dip         .7       -.17
00.3570    0018+84.9        Dip         .7       -.16
00.3573    0018+86.7        Dip        1.3       -.16
00.3579    0018+90.0        Dip         .2       -.15
```

Distance	Station	Type	Width(feet)	Elev(inches)
00.3608	0019+05.2	Bump	1.1	.17
00.3611	0019+06.5	Bump	11.1	.24
00.3645	0019+24.4	Dip	6.0	-.21
00.3657	0019+30.8	Dip	.9	-.17
00.3682	0019+44.2	Bump	.4	.16
00.3683	0019+44.8	Bump	.2	.15
00.3684	0019+45.3	Bump	.4	.15
00.3687	0019+46.8	Bump	3.1	.21
00.3701	0019+54.2	Dip	5.4	-.45
00.3717	0019+62.6	Bump	6.0	.32
00.3753	0019+81.4	Dip	.9	-.18
00.3812	0020+12.5	Bump	5.6	.37
00.3828	0020+21.2	Dip	3.4	-.25
00.3865	0020+40.8	Bump	4.4	.18
00.3874	0020+45.7	Bump	.4	.16
00.3889	0020+53.5	Dip	10.3	-.38
00.3925	0020+72.2	Bump	.7	.16
00.3926	0020+73.1	Bump	4.5	.26
00.3952	0020+86.9	Dip	3.4	-.20
00.3975	0020+98.9	Bump	9.3	.42
00.3999	0021+11.4	Dip	8.2	-.27
00.4015	0021+20.1	Dip	.2	-.15
00.4016	0021+20.5	Dip	.2	-.15
00.4022	0021+23.7	Dip	1.1	-.46
00.4052	0021+39.7	Bump	1.8	.24
00.4153	0021+92.7	Bump	4.0	.24
00.4208	0022+21.7	Dip	3.1	-.20
00.4225	0022+31.0	Bump	4.5	.22
00.4243	0022+40.4	Dip	.5	-.18
00.4263	0022+51.0	Dip	5.6	-.27
00.4287	0022+63.5	Bump	6.4	.23
00.4391	0023+18.7	Bump	.4	.15
00.4449	0023+49.0	Dip	1.1	-.16
00.4459	0023+54.6	Bump	.4	.16
00.4461	0023+55.1	Bump	.2	.15
00.4463	0023+56.2	Bump	4.0	.26
00.4479	0023+65.1	Dip	1.5	-.18
00.4487	0023+68.9	Dip	1.3	-.20
00.4577	0024+16.7	Bump	.9	.16
00.4886	0025+80.0	Dip	4.4	-.22
00.4916	0025+95.6	Bump	.2	.15
00.4984	0026+31.8	Bump	.2	.15
00.4996	0026+38.1	Dip	.9	-.18
00.5020	0026+50.8	Bump	.5	.15
00.5022	0026+51.5	Bump	.7	.16
00.5056	0026+69.5	Dip	.5	-.17
00.5085	0026+84.7	Dip	1.3	-.17
00.5119	0027+02.9	Dip	4.7	-.30
00.5321	0028+09.3	Bump	1.8	.17
00.5426	0028+65.2	Dip	1.8	-.21
00.5456	0028+80.9	Bump	.5	.17
00.5460	0028+83.1	Bump	2.7	.24
00.5488	0028+97.5	Dip	.4	-.15
00.5621	0029+67.7	Dip	1.3	-.17
00.5791	0030+57.5	Dip	1.6	-.18
00.5795	0030+59.9	Dip	2.7	-.19
00.5821	0030+73.7	Bump	4.0	.20
00.5831	0030+78.8	Bump	.5	.16

```
Distance   Station          Type  Width(feet)    Elev(inches)
00.5848    0030+87.5        Dip       2.0        -.17
00.5953    0031+43.0        Dip        .4        -.15
00.5971    0031+52.5        Dip        .4        -.18
00.5988    0031+61.9        Bump      1.1         .19
00.6071    0032+05.3        Bump      1.5         .18
00.6134    0032+38.5        Dip        .4        -.16
00.6135    0032+39.0        Dip        .2        -.15
00.6189    0032+67.7        Dip       6.0        -.26
00.6255    0033+02.4        Bump       .9         .17
00.6391    0033+74.4        Dip       4.2        -.24
00.6400    0033+79.3        Dip        .9        -.18
00.6494    0034+29.1        Bump      4.4         .23
00.6587    0034+78.1        Dip       9.6        -.73
00.6614    0034+92.2        Bump      2.0         .18
00.6620    0034+95.1        Bump      1.8         .25
00.6656    0035+14.6        Bump      8.5         .27
00.6691    0035+33.1        Dip        .7        -.20
00.6712    0035+44.2        Bump       .9         .18
00.6718    0035+47.2        Bump       .7         .16
00.6722    0035+49.1        Bump       .2         .15
00.6760    0035+69.0        Dip       9.3        -.25
00.6887    0036+36.2        Dip        .2        -.15
00.6887    0036+36.5        Dip       1.1        -.16
00.6920    0036+54.0        Dip      10.3        -.39
00.6954    0036+71.6        Bump      3.4         .18
00.7035    0037+14.4        Dip        .4        -.27
00.7042    0037+18.2        Bump      2.0         .30
00.7047    0037+20.8        Bump       .2         .15
00.7073    0037+34.5        Dip       4.4        -.21
00.7119    0037+58.9        Bump      6.5         .25
00.7144    0037+71.9        Bump      1.3         .16
00.7177    0037+89.5        Dip       2.4        -.20
00.7240    0038+22.9        Dip        .2        -.15
Bumps/dips detected  127

Distance Station PSI  IRI(L)  IRI(R)   Avg IRI  Pay*SectLen       Pay
00.1000  5+28.0  3.28 122.57  122.69   123.00  $  0*(0.1000/0.10)   $0
00.2000  10+56.0 3.23 115.95  135.38   126.00  $  0*(0.1000/0.10)   $0
00.3000  15+84.0 3.13 130.34  133.65   132.00  $  0*(0.1000/0.10)   $0
00.4000  21+12.0 2.24 201.61  197.43   200.00  $  0*(0.1000/0.10)   $0
00.5000  26+40.0 2.11 174.49  247.55   211.00  $  0*(0.1000/0.10)   $0
00.6000  31+68.0 2.17 187.56  223.46   206.00  $  0*(0.1000/0.10)   $0
00.7000  36+96.0 2.10 202.62  220.75   212.00  $  0*(0.1000/0.10)   $0
00.7276  38+41.7 1.97 209.38  237.45   223.00  $  0*(0.0277/0.10)   $0
                                          Pay Adjustment Subtotal   $0
Ave Left IRI  164   Ave Right IRI  185.1  Ave IRI  174.55
Total IRI adjustments   $     0
Total Bump adjustments  $     0
Total adjustments       $     0
```

```
Ride Quality Analysis Rel 2006.12.04
Report run on Friday, Jan 8 2010 3:49:42PM
Input profile data file created Tuesday, Dec 15 2009 8:14:16AM

District: 2                                  Highway: RANDOL_MILL RUN1
Area Office: UTA                             Beg RM: 0000 +00.000
County: 220                                  Beg Station: 0000+00.0
Name: MILES HICKS                            CSJ: 0000-00-000
Phone: 214-319-6474                          Lane designation: K6
Input file: t:\dalpme\uta project with profiler\randal mill rd
run1.pro

No Bump penalties assessed.
Total length profile: 0.2726 miles or 0014+39.3 station units.

Distance   Station           Type  Width(feet)   Elev(inches)
00.0045    0000+23.8         Dip        .4       -.158
00.0048    0000+25.1         Dip        .7       -.192
00.0074    0000+39.2         Bump       .2        .160
00.0076    0000+39.9         Bump       .2        .169
00.0091    0000+47.9         Dip       8.5       -.306
00.0114    0000+60.0         Bump      1.8        .256
00.0124    0000+65.4         Bump      2.3        .226
00.0164    0000+86.5         Bump      2.3        .181
00.0169    0000+89.2         Bump       .5        .164
00.0194    0001+02.6         Bump      6.1        .239
00.0206    0001+08.9         Bump       .5        .171
00.0208    0001+09.7         Bump      1.1        .192
00.0215    0001+13.5         Dip      11.0       -.366
00.0247    0001+30.4         Bump      5.4       1.059
00.0301    0001+59.2         Dip       7.8       -.234
00.0322    0001+70.0         Bump      2.5        .180
00.0354    0001+87.0         Bump       .4        .158
00.0357    0001+88.3         Bump      1.3        .174
00.0359    0001+89.7         Bump       .4        .168
00.0387    0002+04.5         Bump       .9        .159
00.0390    0002+05.8         Bump       .2        .159
00.0391    0002+06.3         Bump      5.1        .211
00.0407    0002+14.8         Dip       1.3       -.173
00.0450    0002+37.6         Bump      1.4        .176
00.0461    0002+43.4         Dip       3.4       -.226
00.0496    0002+62.1         Dip        .9       -.162
00.0510    0002+69.4         Bump       .5        .157
00.0590    0003+11.3         Bump      6.5        .313
00.0602    0003+18.0         Bump       .7        .164
00.0610    0003+21.9         Dip       1.8       -.182
00.0640    0003+37.7         Dip       7.4       -.260
00.0668    0003+52.7         Bump      4.7        .199
00.0694    0003+66.4         Bump      3.6        .201
00.0713    0003+76.7         Dip       5.1       -.218
00.0780    0004+11.7         Bump       .4        .155
00.0817    0004+31.4         Bump      4.9        .216
00.0827    0004+36.7         Bump       .7        .157
00.0829    0004+37.6         Bump       .2        .152
00.0830    0004+38.5         Bump      1.1        .184
00.0854    0004+50.9         Dip        .4       -.151
00.0855    0004+51.7         Dip        .2       -.155
00.0857    0004+52.8         Dip       1.8       -.221
00.0877    0004+63.0         Dip        .4       -.176
```

Distance	Station	Type	Width(feet)	Elev(inches)
00.0895	0004+72.6	Dip	5.8	-.431
00.0911	0004+80.8	Bump	.2	.151
00.0911	0004+81.1	Bump	7.0	.208
00.0949	0005+01.0	Bump	.4	.160
00.0952	0005+02.8	Bump	.2	.152
00.0953	0005+03.2	Bump	.5	.163
00.0983	0005+19.1	Bump	1.8	.203
00.0996	0005+25.7	Dip	6.0	-.240
00.1028	0005+42.9	Bump	.4	.178
00.1030	0005+44.0	Bump	.7	.178
00.1089	0005+75.2	Dip	.9	-.176
00.1111	0005+86.4	Bump	.5	.153
00.1118	0005+90.1	Bump	1.3	.188
00.1121	0005+92.0	Bump	.5	.160
00.1135	0005+99.1	Dip	2.7	-.256
00.1140	0006+02.2	Dip	.2	-.158
00.1164	0006+14.8	Bump	.5	.159
00.1166	0006+15.7	Bump	.5	.166
00.1256	0006+63.2	Dip	.5	-.160
00.1258	0006+64.1	Dip	1.4	-.187
00.1318	0006+95.7	Bump	2.0	.203
00.1338	0007+06.6	Bump	.2	.152
00.1339	0007+07.1	Bump	.7	.152
00.1343	0007+08.9	Bump	5.1	.546
00.1356	0007+15.8	Dip	5.2	-.332
00.1369	0007+23.0	Bump	8.9	.435
00.1391	0007+34.6	Dip	14.6	-.486
00.1422	0007+50.9	Bump	.5	.172
00.1428	0007+53.7	Bump	9.2	.383
00.1549	0008+18.1	Bump	2.9	.281
00.1561	0008+24.0	Dip	.4	-.166
00.1740	0009+18.5	Dip	.5	-.158
00.1742	0009+19.6	Dip	3.4	-.203
00.1751	0009+24.5	Dip	2.3	-.203
00.1763	0009+30.6	Bump	4.0	.239
00.1842	0009+72.7	Dip	1.6	-.172
00.1849	0009+76.1	Bump	6.3	.467
00.1863	0009+83.7	Dip	1.3	-.173
00.1870	0009+87.2	Dip	2.7	-.183
00.1905	0010+05.6	Dip	2.2	-.171
00.2013	0010+62.7	Dip	.2	-.155
00.2032	0010+72.8	Bump	1.1	.188
00.2040	0010+77.0	Bump	.4	.156
00.2054	0010+84.5	Bump	1.3	.174
00.2060	0010+87.4	Bump	1.4	.185
00.2084	0011+00.3	Dip	.2	-.167
00.2086	0011+01.5	Dip	.2	-.154
00.2208	0011+66.0	Bump	.2	.151
00.2209	0011+66.4	Bump	1.8	.199
00.2271	0011+98.9	Dip	3.8	-.259
00.2298	0012+13.4	Bump	.4	.161
00.2299	0012+14.1	Bump	3.8	.219
00.2312	0012+20.6	Bump	9.6	.405
00.2335	0012+33.1	Dip	10.7	-.549
00.2364	0012+48.2	Bump	2.5	.244
00.2402	0012+68.5	Bump	.4	.154
00.2404	0012+69.2	Bump	.4	.159
00.2405	0012+69.9	Bump	.5	.171

```
Distance   Station          Type  Width(feet)   Elev(inches)
00.2573    0013+58.6        Dip        .4       -.159
00.2574    0013+59.2        Dip       4.9       -.202
00.2591    0013+68.2        Bump      6.1        .332
00.2630    0013+88.6        Bump       .9        .170
00.2654    0014+01.1        Bump      1.1        .177
00.2661    0014+05.0        Dip       5.6       -.236
00.2706    0014+28.7        Bump      3.1        .257
Total bumps/dips detected: 108

Distance Station PSI  IRI(L)  IRI(R)  Avg IRI  Pay*SectionLength   Pay
00.1000  5+28.0  1.24 257.67  338.31  298.00 -$        Corrective Work
00.2000  10+56.0 1.62 214.94  300.44  258.00 -$        Corrective Work
00.2726  14+39.3 1.42 245.70  311.12  278.00 -$        Corrective Work
                                      Pay Adjustment Subtotal=  $    0
Ave Left IRI: 238.8   Ave Right IRI: 317.2  Ave IRI: 278
Total IRI adjustments: $0
No bump adjustments applied.
```

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Ride Quality Analysis Rel 2006.12.04
Report run on Friday, Jan 8 2010 3:50:38PM
Input profile data file created Tuesday, Dec 15 2009 8:12:00AM

District: 2                                  Highway: RANDOL_MILL RUN2
Area Office: UTA                             Beg RM: 0000 +00.000
County: 220                                  Beg Station: 0000+00.0
Name: MILES HICKS                            CSJ: 0000-00-000
Phone: 214-319-6474                          Lane designation: K8
Input file: t:\dalpme\uta project with profiler\randal mill rd
run2.pro

No Bump penalties assessed.
Total length profile: 0.271 miles or 0014+30.9 station units.

Distance   Station           Type  Width(feet)   Elev(inches)
00.0054    0000+28.4         Dip       2.2       -.236
00.0081    0000+42.8         Bump      1.6        .271
00.0087    0000+45.9         Dip        .2       -.151
00.0088    0000+46.3         Dip        .2       -.154
00.0089    0000+46.8         Dip        .2       -.152
00.0090    0000+47.3         Dip        .5       -.174
00.0100    0000+52.8         Dip       8.1       -.329
00.0121    0000+63.8         Bump      2.3        .265
00.0132    0000+69.9         Bump      2.5        .264
00.0172    0000+91.1         Bump      2.3        .178
00.0178    0000+93.8         Bump       .5        .169
00.0179    0000+94.5         Bump       .2        .152
00.0203    0001+07.3         Bump      6.0        .223
00.0217    0001+14.7         Bump       .9        .192
00.0224    0001+18.2         Dip      10.8       -.364
00.0255    0001+34.8         Bump      5.8        .351
00.0310    0001+63.5         Dip        .4       -.151
00.0311    0001+64.0         Dip       1.1       -.175
00.0313    0001+65.5         Dip       1.4       -.177
00.0317    0001+67.3         Dip       4.5       -.225
00.0331    0001+74.9         Bump      1.1        .171
00.0366    0001+93.3         Bump       .5        .159
00.0369    0001+94.8         Bump       .2        .152
00.0401    0002+11.6         Bump      4.9        .217
00.0417    0002+20.4         Dip        .5       -.158
00.0455    0002+40.1         Bump       .2        .152
00.0459    0002+42.5         Bump      2.2        .201
00.0471    0002+48.6         Dip       2.9       -.210
00.0520    0002+74.4         Bump       .7        .169
00.0599    0003+16.5         Bump      7.9        .302
00.0620    0003+27.5         Dip       1.4       -.164
00.0650    0003+43.1         Dip       7.6       -.258
00.0678    0003+57.9         Bump      4.0        .202
00.0686    0003+62.4         Bump       .2        .154
00.0704    0003+71.5         Bump      2.5        .193
00.0709    0003+74.2         Bump       .9        .157
00.0724    0003+82.1         Dip       5.6       -.210
00.0790    0004+17.0         Bump       .2        .151
00.0827    0004+36.9         Bump      5.1        .207
00.0838    0004+42.3         Bump       .2        .151
00.0839    0004+43.2         Bump       .2        .151
00.0841    0004+43.9         Bump      1.1        .178
00.0867    0004+57.8         Dip       1.8       -.242
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Distance    Station          Type  Width(feet)   Elev(inches)
00.0887     0004+68.3        Dip        .5       -.187
00.0905     0004+78.0        Dip       5.8       -.427
00.0920     0004+85.8        Bump      5.4        .235
00.0931     0004+91.4        Bump       .2        .155
00.0932     0004+92.0        Bump      1.4        .171
00.0959     0005+06.2        Bump       .5        .162
00.0960     0005+07.0        Bump       .2        .152
00.0963     0005+08.2        Bump       .2        .153
00.0994     0005+24.7        Bump      1.6        .224
00.1006     0005+31.2        Dip       6.0       -.254
00.1040     0005+49.2        Bump       .7        .195
00.1100     0005+80.8        Dip        .4       -.153
00.1119     0005+90.8        Bump      1.1        .162
00.1121     0005+92.0        Bump       .4        .153
00.1128     0005+95.7        Bump      2.9        .191
00.1143     0006+03.2        Dip       4.5       -.252
00.1173     0006+19.3        Bump       .2        .156
00.1174     0006+20.0        Bump       .7        .156
00.1176     0006+21.0        Bump       .5        .161
00.1265     0006+68.1        Dip       2.5       -.177
00.1340     0007+07.7        Dip        .4       -.159
00.1346     0007+10.6        Bump      8.5        .472
00.1365     0007+20.9        Dip       5.2       -.359
00.1380     0007+28.4        Bump      8.7        .393
00.1401     0007+39.8        Dip      14.6       -.463
00.1432     0007+55.9        Bump       .5        .166
00.1437     0007+58.6        Bump      9.4        .385
00.1559     0008+23.1        Bump      2.9        .272
00.1570     0008+29.1        Dip        .2       -.159
00.1749     0009+23.4        Dip        .7       -.154
00.1751     0009+24.5        Dip       3.4       -.195
00.1760     0009+29.3        Dip       2.3       -.205
00.1772     0009+35.5        Bump      3.8        .256
00.1780     0009+40.0        Bump       .4        .157
00.1851     0009+77.6        Dip       1.6       -.180
00.1858     0009+81.0        Bump      6.1        .464
00.1879     0009+92.0        Dip       2.7       -.198
00.1913     0010+09.9        Dip       2.9       -.196
00.2041     0010+77.9        Bump       .2        .151
00.2049     0010+81.7        Bump       .5        .174
00.2063     0010+89.2        Bump      1.1        .171
00.2068     0010+91.9        Bump      1.8        .197
00.2094     0011+05.9        Dip        .5       -.164
00.2159     0011+40.2        Dip        .4       -.156
00.2218     0011+70.9        Bump      1.8        .218
00.2237     0011+81.4        Dip        .2       -.152
00.2280     0012+03.6        Dip       3.4       -.260
00.2307     0012+17.9        Bump      4.0        .248
00.2318     0012+23.7        Bump       .2        .153
00.2321     0012+25.5        Bump      9.4        .403
00.2344     0012+37.6        Dip      10.7       -.540
00.2373     0012+52.7        Bump      2.2        .252
00.2412     0012+73.7        Bump       .5        .177
00.2414     0012+74.4        Bump       .7        .183
00.2584     0013+64.4        Dip       4.3       -.198
00.2601     0013+73.2        Bump      5.8        .385
00.2639     0013+93.3        Bump       .4        .162
00.2663     0014+05.9        Bump       .9        .176
```

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Distance   Station           Type  Width(feet)   Elev(inches)
00.2669    0014+09.2         Dip       6.1       -.237
Total bumps/dips detected: 102

Distance Station PSI   IRI(L)  IRI(R) Avg IRI  Pay*SectionLength   Pay
00.1000  5+28.0  1.19  259.95  347.92 304.00 -$        Corrective Work
00.2000  10+56.0 1.66  210.48  296.91 254.00 -$        Corrective Work
00.2710  14+30.9 1.55  234.09  296.64 265.00 -$        Corrective Work
                                      Pay Adjustment Subtotal=  $    0
Ave Left IRI: 234.9   Ave Right IRI: 315.7  Ave IRI: 275.3
Total IRI adjustments: $0
No bump adjustments applied.
```

```
Ride Quality Analysis Rel 2006.12.04
Report run on Friday, Jan 8 2010 3:50:57PM
Input profile data file created Tuesday, Dec 15 2009 8:17:16AM

District: 2                               Highway: RD_TO_SIX_FLAGS RUN1
Area Office: UTA                          Beg RM: 0000 +00.000
County: 220                               Beg Station: 0000+00.0
Name: MILES HICKS                         CSJ: 0000-00-000
Phone: 214-319-6474                       Lane designation: K8
Input file: t:\dalpme\uta project with profiler\rd to six flags
run1.pro

No Bump penalties assessed.
Total length profile: 0.2963 miles or 0015+64.5 station units.

Distance   Station           Type  Width(feet)   Elev(inches)
00.0027    0000+14.1         Bump       .2         .154
00.0027    0000+14.5         Bump       .2         .162
00.0028    0000+14.8         Bump      2.0         .312
00.0037    0000+19.7         Dip       7.9        -.308
00.0053    0000+27.8         Dip        .7        -.266
00.0057    0000+30.4         Bump       .4         .186
00.0064    0000+34.0         Bump      6.1         .252
00.0144    0000+76.2         Dip       5.1        -.227
00.0154    0000+81.5         Dip        .7        -.168
00.0252    0001+33.2         Dip       1.6        -.183
00.0275    0001+45.1         Bump       .9         .168
00.0284    0001+49.8         Bump       .4         .170
00.0285    0001+50.5         Bump      1.6         .173
00.0288    0001+52.3         Bump       .4         .165
00.0289    0001+52.8         Bump      6.7         .216
00.0346    0001+82.8         Bump      4.9         .244
00.0364    0001+92.2         Dip      14.1        -.487
00.0394    0002+08.1         Bump       .2         .154
00.0400    0002+11.2         Bump      3.4         .313
00.0439    0002+31.8         Bump       .2         .153
00.0440    0002+32.2         Bump       .9         .167
00.0453    0002+39.2         Dip        .2        -.156
00.0454    0002+39.7         Dip        .4        -.156
00.0495    0002+61.2         Dip       4.0        -.203
00.0520    0002+74.6         Bump       .5         .193
00.0521    0002+75.3         Bump      2.3         .205
00.0527    0002+78.4         Bump       .7         .167
00.0529    0002+79.3         Bump       .5         .185
00.0541    0002+85.8         Dip        .2        -.151
00.0565    0002+98.5         Bump      2.3         .172
00.0635    0003+35.5         Bump       .2         .155
00.0639    0003+37.5         Bump      1.1         .184
00.0655    0003+46.0         Bump      2.5         .211
00.0666    0003+51.6         Bump       .2         .152
00.0674    0003+55.7         Dip        .2        -.151
00.0678    0003+58.1         Dip       1.8        -.233
00.0682    0003+60.1         Dip        .4        -.155
00.0700    0003+69.6         Bump      2.9         .246
00.0716    0003+78.0         Dip        .2        -.291
00.0720    0003+80.3         Dip        .4        -.212
00.0723    0003+81.6         Dip        .5        -.172
00.0724    0003+82.3         Dip       1.4        -.182
00.0727    0003+83.9         Dip       4.9        -.227
```

Distance	Station	Type	Width(feet)	Elev(inches)
00.0747	0003+94.4	Bump	5.2	.278
00.0765	0004+04.2	Dip	7.0	-.306
00.0803	0004+23.8	Bump	3.3	.181
00.0902	0004+76.2	Bump	1.1	.186
00.0913	0004+82.2	Bump	.7	.160
00.0952	0005+02.8	Dip	.9	-.204
00.0954	0005+03.9	Dip	2.3	-.188
00.0962	0005+07.7	Dip	.9	-.176
00.0964	0005+08.9	Dip	1.6	-.188
00.0979	0005+16.7	Bump	.4	.164
00.0980	0005+17.2	Bump	6.0	.594
00.0994	0005+24.7	Dip	3.3	-.736
00.1001	0005+28.3	Dip	.2	-.160
00.1011	0005+33.9	Bump	.5	.186
00.1015	0005+35.7	Dip	8.9	-.433
00.1036	0005+47.2	Bump	3.3	.261
00.1044	0005+51.4	Bump	1.4	.209
00.1048	0005+53.2	Bump	.2	.152
00.1048	0005+53.6	Bump	3.4	.251
00.1061	0005+60.2	Bump	4.3	.200
00.1074	0005+67.1	Dip	6.0	-.237
00.1095	0005+78.1	Bump	2.7	.224
00.1177	0006+21.5	Dip	2.7	-.185
00.1183	0006+24.6	Dip	.2	-.152
00.1192	0006+29.3	Bump	3.8	.223
00.1254	0006+62.1	Bump	7.4	.334
00.1272	0006+71.7	Bump	.2	.154
00.1280	0006+75.7	Dip	1.1	-.174
00.1309	0006+91.2	Bump	1.3	.190
00.1312	0006+92.7	Bump	.2	.159
00.1327	0007+00.6	Dip	.2	-.152
00.1337	0007+05.9	Bump	.9	.173
00.1345	0007+10.2	Bump	.7	.159
00.1354	0007+14.7	Dip	6.9	-.418
00.1372	0007+24.3	Bump	2.3	.191
00.1382	0007+29.5	Bump	.9	.169
00.1385	0007+31.5	Bump	.4	.154
00.1417	0007+48.3	Bump	2.3	.174
00.1422	0007+50.9	Bump	.2	.152
00.1447	0007+64.0	Dip	1.4	-.313
00.1450	0007+65.8	Dip	4.7	-.283
00.1461	0007+71.4	Dip	.2	-.151
00.1473	0007+77.8	Dip	.2	-.154
00.1483	0007+83.0	Bump	.7	.172
00.1489	0007+86.4	Bump	4.7	.245
00.1503	0007+93.5	Bump	4.7	.365
00.1517	0008+00.9	Dip	.5	-.182
00.1519	0008+01.8	Dip	.2	-.151
00.1521	0008+02.9	Dip	6.5	-.284
00.1543	0008+14.8	Bump	4.7	.256
00.1559	0008+23.1	Dip	4.2	-.181
00.1594	0008+41.7	Bump	2.7	.447
00.1631	0008+61.2	Dip	3.3	-.193
00.1638	0008+64.9	Dip	1.4	-.352
00.1714	0009+05.0	Dip	2.2	-.204
00.1733	0009+15.3	Bump	3.4	.388
00.1747	0009+22.3	Dip	.4	-.158
00.1748	0009+22.8	Dip	2.9	-.228

Distance	Station	Type	Width(feet)	Elev(inches)
00.1794	0009+47.1	Bump	1.8	.354
00.1798	0009+49.2	Bump	1.6	.216
00.1809	0009+55.2	Dip	4.0	-.247
00.1828	0009+64.9	Bump	.2	.152
00.1832	0009+67.3	Bump	5.1	.269
00.1842	0009+72.5	Bump	.2	.162
00.1872	0009+88.2	Bump	3.3	.314
00.1888	0009+96.9	Dip	1.3	-.181
00.1898	0010+02.2	Dip	1.4	-.174
00.1907	0010+06.7	Bump	7.9	.384
00.1930	0010+19.0	Dip	5.6	-.458
00.1947	0010+27.8	Bump	4.5	.263
00.1968	0010+39.2	Dip	4.5	-.218
00.1978	0010+44.4	Dip	.2	-.158
00.1983	0010+46.8	Bump	4.3	.393
00.2003	0010+57.4	Dip	5.6	-.319
00.2029	0010+71.4	Dip	3.3	-.254
00.2059	0010+87.1	Dip	1.1	-.176
00.2068	0010+91.8	Bump	3.3	.255
00.2085	0011+00.6	Dip	.5	-.178
00.2108	0011+12.9	Bump	2.5	.224
00.2120	0011+19.6	Bump	1.6	.261
00.2147	0011+33.7	Bump	2.0	.205
00.2189	0011+55.9	Dip	.2	-.162
00.2195	0011+58.8	Bump	5.1	.227
00.2215	0011+69.3	Dip	3.3	-.234
00.2233	0011+79.2	Bump	6.5	.255
00.2258	0011+92.4	Dip	4.7	-.325
00.2320	0012+25.1	Bump	.7	.170
00.2338	0012+34.5	Bump	2.5	.252
00.2379	0012+56.4	Dip	8.1	-.333
00.2401	0012+67.7	Bump	9.2	.266
00.2435	0012+85.4	Bump	.9	.167
00.2444	0012+90.5	Dip	.7	-.154
00.2449	0012+93.0	Dip	.9	-.177
00.2451	0012+94.1	Dip	.2	-.151
00.2452	0012+94.7	Dip	2.5	-.196
00.2494	0013+16.9	Bump	2.9	.208
00.2529	0013+35.3	Dip	.7	-.172
00.2551	0013+46.7	Bump	.5	.156
00.2553	0013+47.8	Bump	.2	.154
00.2554	0013+48.3	Bump	.5	.156
00.2640	0013+93.7	Dip	.2	-.157
00.2641	0013+94.6	Dip	8.3	-.249
00.2666	0014+07.8	Bump	9.9	.354
00.2690	0014+20.6	Dip	6.9	-.369
00.2726	0014+39.6	Dip	.7	-.176
00.2743	0014+48.2	Bump	1.4	.189
00.2746	0014+50.0	Bump	5.8	.306
00.2762	0014+58.5	Dip	4.7	-.280
00.2772	0014+63.4	Dip	.2	-.156
00.2772	0014+63.8	Dip	.2	-.158
00.2773	0014+64.3	Dip	1.3	-.177
00.2783	0014+69.4	Bump	.2	.160
00.2784	0014+69.7	Bump	2.2	.169
00.2789	0014+72.4	Bump	1.1	.167
00.2791	0014+73.7	Bump	1.4	.256
00.2804	0014+80.4	Bump	.2	.156

```
Distance   Station          Type  Width(feet)   Elev(inches)
00.2805    0014+80.9        Bump      .4         .157
00.2806    0014+81.5        Bump     1.4         .181
00.2820    0014+88.9        Dip       .2        -.153
00.2821    0014+89.6        Dip      5.6        -.416
00.2849    0015+04.2        Bump      .2         .151
00.2850    0015+05.0        Bump     1.4         .179
00.2854    0015+06.8        Bump      .9         .175
00.2868    0015+14.5        Dip      4.7        -.202
00.2886    0015+23.9        Bump     6.7         .269
00.2911    0015+36.9        Dip       .4        -.170
00.2912    0015+37.7        Dip       .2        -.164
00.2914    0015+38.4        Dip       .2        -.165
00.2916    0015+39.8        Dip       .7        -.162
00.2921    0015+42.2        Dip      1.3        -.169
00.2939    0015+51.7        Bump     1.4         .172
Total bumps/dips detected: 174

Distance Station  PSI  IRI(L)  IRI(R) Avg IRI  Pay*SectionLength   Pay
00.1000  5+28.0  1.49  252.54  289.22 271.00 -$        Corrective Work
00.2000  10+56.0  .70  362.96  362.09 363.00 -$        Corrective Work
00.2963  15+64.5 1.06  318.92  318.58 319.00 -$        Corrective Work
                                      Pay Adjustment Subtotal=  $    0
Ave Left IRI: 311.4   Ave Right IRI: 323.4  Ave IRI: 317.4
Total IRI adjustments: $0
No bump adjustments applied.
```

```
Ride Quality Analysis Rel 2006.12.04
Report run on Friday, Jan 8 2010 3:51:26PM
Input profile data file created Tuesday, Dec 15 2009 8:17:42AM

District: 2                               Highway: RD_TO_SIX_FLAGS RUN2
Area Office: UTA                          Beg RM: 0000 +00.000
County: 220                               Beg Station: 0000+00.0
Name: MILES HICKS                         CSJ: 0000-00-000
Phone: 214-319-6474                       Lane designation: K8
Input file: t:\dalpme\uta project with profiler\rd to six flags
run2.pro

No Bump penalties assessed.
Total length profile: 0.2902 miles or 0015+32.3 station units.

Distance   Station          Type  Width(feet)   Elev(inches)
00.0007    0000+03.8        Bump        .4          .179
00.0020    0000+10.3        Bump        .2          .151
00.0020    0000+10.7        Bump       3.6          .243
00.0069    0000+36.3        Bump       1.3          .191
00.0072    0000+37.9        Bump        .4          .179
00.0074    0000+38.8        Bump        .5          .169
00.0093    0000+49.3        Dip        6.0         -.224
00.0202    0001+06.8        Dip        1.3         -.166
00.0232    0001+22.7        Dip         .2         -.161
00.0233    0001+23.0        Bump        .4          .189
00.0234    0001+23.6        Bump       1.8          .182
00.0238    0001+25.6        Bump       7.4          .209
00.0295    0001+55.9        Bump       5.2          .266
00.0315    0001+66.4        Dip       13.2         -.510
00.0350    0001+84.6        Bump       3.6          .320
00.0389    0002+05.4        Bump        .2          .157
00.0403    0002+13.0        Dip         .5         -.160
00.0446    0002+35.2        Dip        2.9         -.215
00.0451    0002+38.3        Dip         .2         -.155
00.0469    0002+47.9        Bump        .7          .192
00.0471    0002+48.8        Bump       1.3          .191
00.0474    0002+50.2        Bump        .4          .156
00.0477    0002+51.7        Bump        .2          .151
00.0478    0002+52.2        Bump       1.1          .185
00.0491    0002+59.3        Dip         .2         -.156
00.0515    0002+71.9        Bump       1.6          .178
00.0518    0002+73.7        Bump        .4          .159
00.0585    0003+08.8        Bump        .2          .151
00.0589    0003+11.1        Bump       1.1          .198
00.0603    0003+18.5        Bump       3.6          .259
00.0615    0003+24.7        Bump        .5          .174
00.0621    0003+27.9        Dip        6.5         -.270
00.0640    0003+38.0        Dip         .2         -.154
00.0642    0003+38.9        Dip         .2         -.161
00.0657    0003+46.9        Bump       2.3          .185
00.0662    0003+49.4        Bump        .9          .169
00.0664    0003+50.7        Bump        .7          .174
00.0672    0003+54.8        Dip         .4         -.339
00.0677    0003+57.4        Dip        1.1         -.270
00.0693    0003+65.7        Dip         .7         -.361
00.0695    0003+66.8        Dip         .9         -.645
00.0699    0003+69.1        Bump       4.2          .255
00.0715    0003+77.4        Dip        7.0         -.381
```

Distance	Station	Type	Width(feet)	Elev(inches)
00.0749	0003+95.5	Bump	.2	.153
00.0752	0003+97.1	Bump	3.3	.199
00.0852	0004+49.9	Bump	.9	.198
00.0902	0004+76.4	Dip	3.4	-.263
00.0910	0004+80.4	Dip	.2	-.156
00.0913	0004+82.0	Dip	.2	-.154
00.0927	0004+89.6	Bump	.5	.159
00.0929	0004+90.3	Bump	3.6	.578
00.0936	0004+94.1	Bump	2.3	.332
00.0943	0004+98.1	Dip	3.4	-1.477
00.0953	0005+03.0	Bump	2.0	.260
00.0965	0005+09.5	Dip	1.3	-.255
00.0971	0005+12.6	Dip	5.2	-.424
00.0990	0005+22.7	Bump	3.1	.265
00.0998	0005+27.0	Bump	.2	.156
00.0999	0005+27.4	Bump	3.1	.236
00.1010	0005+33.3	Bump	4.9	.191
00.1024	0005+40.6	Dip	6.3	-.250
00.1045	0005+51.8	Bump	.2	.153
00.1046	0005+52.1	Bump	2.2	.217
00.1127	0005+95.1	Dip	1.4	-.181
00.1131	0005+96.9	Dip	.7	-.163
00.1141	0006+02.7	Bump	3.3	.231
00.1148	0006+06.1	Bump	.4	.170
00.1195	0006+30.9	Dip	.7	-.163
00.1204	0006+35.6	Bump	7.8	.346
00.1222	0006+45.2	Bump	.4	.163
00.1229	0006+49.1	Dip	1.3	-.176
00.1234	0006+51.3	Dip	.2	-.152
00.1259	0006+64.7	Bump	1.4	.188
00.1277	0006+74.1	Dip	.7	-.173
00.1278	0006+75.0	Dip	.2	-.151
00.1287	0006+79.3	Bump	.9	.182
00.1295	0006+83.6	Bump	1.3	.168
00.1304	0006+88.3	Dip	6.7	-.427
00.1319	0006+96.7	Bump	3.4	.219
00.1330	0007+02.1	Bump	.2	.151
00.1330	0007+02.4	Bump	1.4	.187
00.1335	0007+05.0	Bump	.4	.153
00.1345	0007+10.4	Dip	.5	-.156
00.1368	0007+22.5	Bump	.2	.156
00.1369	0007+22.8	Bump	.9	.164
00.1396	0007+37.3	Dip	1.4	-.324
00.1400	0007+39.3	Dip	4.9	-.288
00.1410	0007+44.5	Dip	.5	-.167
00.1423	0007+51.6	Dip	.2	-.151
00.1432	0007+56.1	Bump	.2	.152
00.1433	0007+56.5	Bump	.9	.178
00.1440	0007+60.1	Bump	4.5	.235
00.1452	0007+66.6	Bump	4.9	.361
00.1466	0007+74.0	Dip	1.8	-.183
00.1470	0007+76.0	Dip	6.7	-.307
00.1492	0007+87.7	Bump	5.4	.236
00.1509	0007+96.7	Dip	4.3	-.241
00.1524	0008+04.9	Bump	.4	.163
00.1544	0008+15.2	Bump	2.7	.420
00.1581	0008+34.9	Dip	2.7	-.198
00.1588	0008+38.5	Dip	1.1	-.343

Distance	Station	Type	Width(feet)	Elev(inches)
00.1663	0008+78.0	Dip	2.2	-.215
00.1683	0008+88.5	Bump	3.6	.376
00.1696	0008+95.7	Dip	3.4	-.226
00.1744	0009+20.7	Bump	1.6	.301
00.1747	0009+22.5	Bump	1.8	.254
00.1758	0009+28.4	Dip	2.3	-.201
00.1764	0009+31.2	Dip	1.4	-.173
00.1781	0009+40.4	Bump	2.2	.194
00.1786	0009+43.3	Bump	1.1	.214
00.1822	0009+62.1	Bump	.9	.178
00.1824	0009+63.3	Bump	.2	.151
00.1825	0009+63.9	Bump	.2	.158
00.1834	0009+68.6	Dip	.9	-.175
00.1836	0009+69.6	Dip	4.0	-.205
00.1849	0009+76.1	Dip	.2	-.157
00.1856	0009+80.1	Bump	8.3	.459
00.1872	0009+88.6	Bump	.7	.187
00.1874	0009+89.5	Bump	1.6	.204
00.1879	0009+92.2	Dip	5.4	-.816
00.1894	0010+99.8	Bump	5.6	.301
00.1933	0010+20.8	Dip	.2	-.155
00.1937	0010+22.6	Bump	1.1	.239
00.1943	0010+26.0	Dip	.7	-.182
00.1953	0010+31.2	Dip	4.9	-.265
00.1983	0010+47.1	Dip	.4	-.161
00.2012	0010+62.1	Dip	.4	-.157
00.2018	0010+65.4	Bump	6.5	.255
00.2035	0010+74.2	Dip	1.6	-.183
00.2042	0010+78.2	Dip	1.1	-.164
00.2059	0010+87.3	Bump	1.8	.229
00.2070	0010+93.0	Bump	.5	.176
00.2082	0010+99.2	Dip	.4	-.165
00.2083	0011+99.7	Dip	.5	-.165
00.2096	0011+06.9	Bump	2.3	.231
00.2139	0011+29.3	Dip	.2	-.152
00.2145	0011+32.6	Bump	5.2	.262
00.2163	0011+42.2	Dip	4.2	-.285
00.2184	0011+53.0	Bump	6.5	.283
00.2209	0011+66.6	Dip	3.4	-.398
00.2254	0011+90.1	Dip	1.3	-.194
00.2257	0011+91.7	Dip	.2	-.152
00.2270	0011+98.7	Bump	.7	.171
00.2288	0012+07.9	Bump	2.3	.252
00.2329	0012+29.8	Dip	8.1	-.311
00.2351	0012+41.4	Bump	9.2	.261
00.2386	0012+59.6	Bump	.4	.155
00.2399	0012+66.7	Dip	2.2	-.184
00.2404	0012+69.5	Dip	1.3	-.172
00.2444	0012+90.7	Bump	2.9	.207
00.2480	0013+09.5	Dip	.4	-.154
00.2481	0013+10.2	Dip	.2	-.151
00.2504	0013+22.1	Bump	.5	.163
00.2531	0013+36.6	Dip	.2	-.165
00.2586	0013+65.5	Dip	.7	-.216
00.2589	0013+67.1	Dip	.2	-.151
00.2590	0013+67.6	Dip	9.4	-.253
00.2617	0013+81.7	Bump	9.9	.332
00.2641	0013+94.4	Dip	7.9	-.372

```
Distance   Station           Type  Width(feet)   Elev(inches)
00.2694    0014+22.2         Bump      1.1        .173
00.2696    0014+23.5         Bump       .4        .159
00.2697    0014+24.0         Bump      5.8        .304
00.2712    0014+31.8         Dip       7.8       -.284
00.2734    0014+43.3         Bump      6.0        .244
00.2746    0014+49.7         Bump       .4        .175
00.2755    0014+54.5         Bump      1.3        .172
00.2758    0014+56.2         Bump       .5        .158
00.2769    0014+62.0         Dip        .4       -.169
00.2770    0014+62.5         Dip        .9       -.183
00.2772    0014+63.6         Dip       4.9       -.398
00.2802    0014+79.3         Bump       .9        .167
00.2804    0014+80.4         Bump      1.6        .181
00.2819    0014+88.3         Dip       6.0       -.206
00.2837    0014+98.1         Bump      6.1        .285
00.2862    0015+11.3         Dip       1.4       -.175
00.2872    0015+16.3         Dip        .4       -.156
00.2873    0015+16.9         Dip        .4       -.162
00.2874    0015+17.4         Dip        .2       -.156
Total bumps/dips detected: 178

Distance Station PSI  IRI(L)  IRI(R) Avg IRI  Pay*SectionLength    Pay
00.1000  5+28.0  1.16 273.44  341.58 308.00 -$       Corrective Work
00.2000  10+56.0  .71 370.01  354.11 362.00 -$       Corrective Work
00.2902  15+32.3 1.08 314.27  318.92 317.00 -$       Corrective Work
                                      Pay Adjustment Subtotal=  $    0
Ave Left IRI: 319.4   Ave Right IRI: 338.9  Ave IRI: 329.15
Total IRI adjustments: $0
No bump adjustments applied.
```

APPENDIX B

SURVEYS OF LONGITUDINAL PROFILE

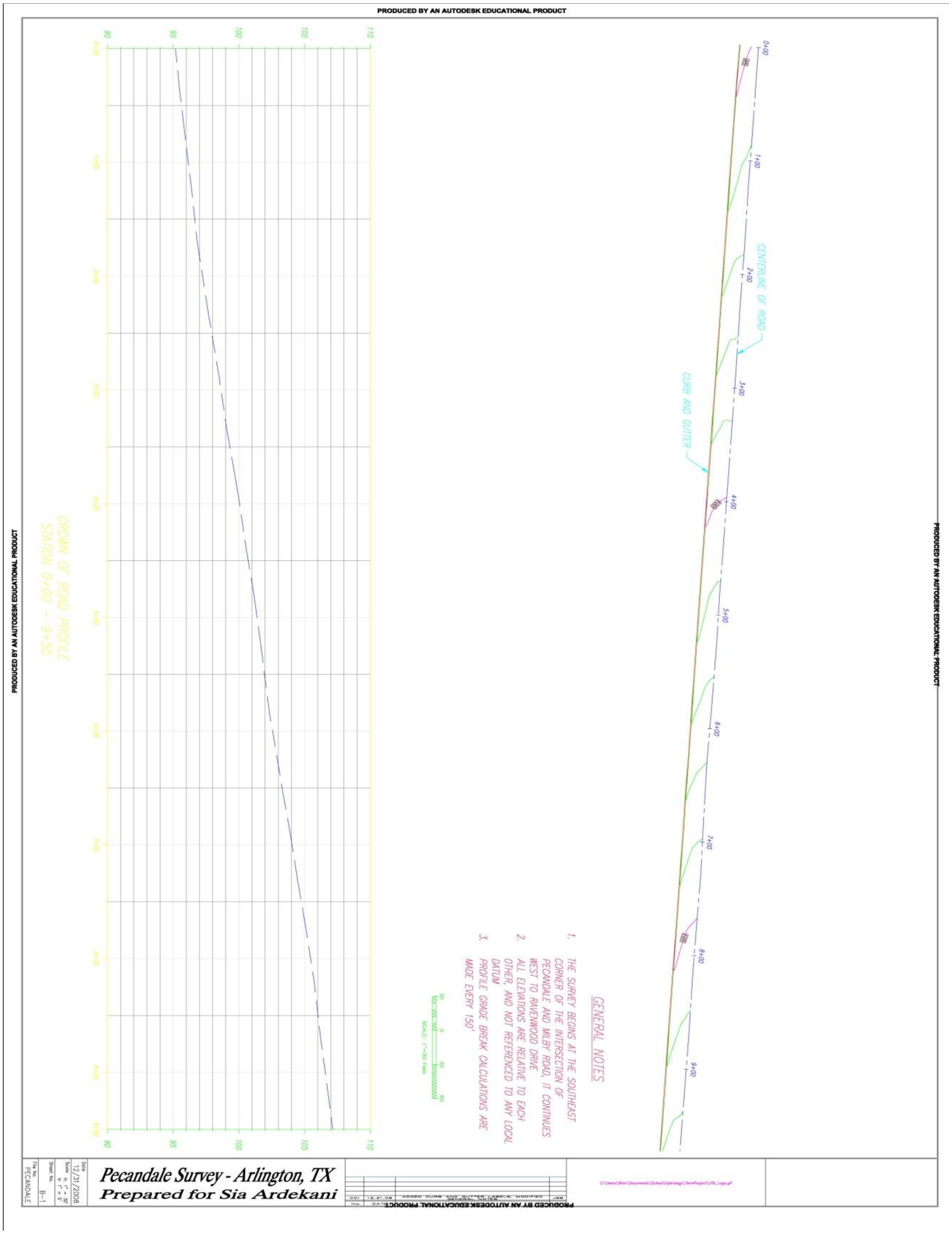
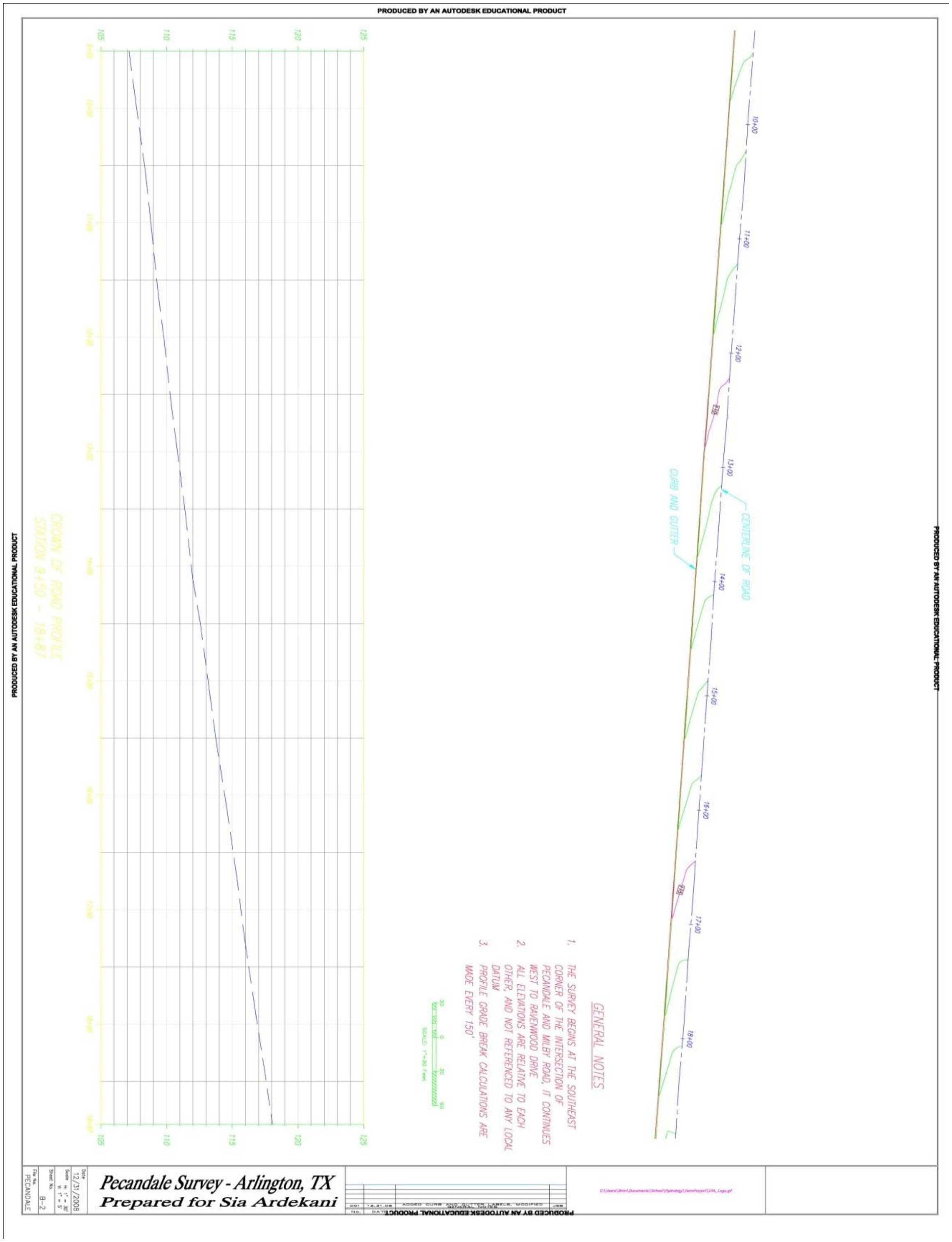


Exhibit B-1 Longitudinal Grade for Pecandale Drive (AC) in Arlington, TX (Part 1).



GENERAL NOTES

1. THE SURVEY BEGINS AT THE SOUTHEAST CORNER OF THE INTERSECTION OF PECANDALE AND MILBY ROAD, IT CONTINUES WEST TO RAVENWOOD DRIVE
2. ALL ELEVATIONS ARE RELATIVE TO EACH OTHER, AND NOT REFERENCED TO ANY LOCAL DATUM
3. PROFILE GRADE BREAK CALCULATIONS ARE MADE EVERY 150'

Pecandale Survey - Arlington, TX
Prepared for Sia Ardekani

Exhibit B-2 Longitudinal Grade for Pecandale Drive (AC) in Arlington, TX (Part 2).

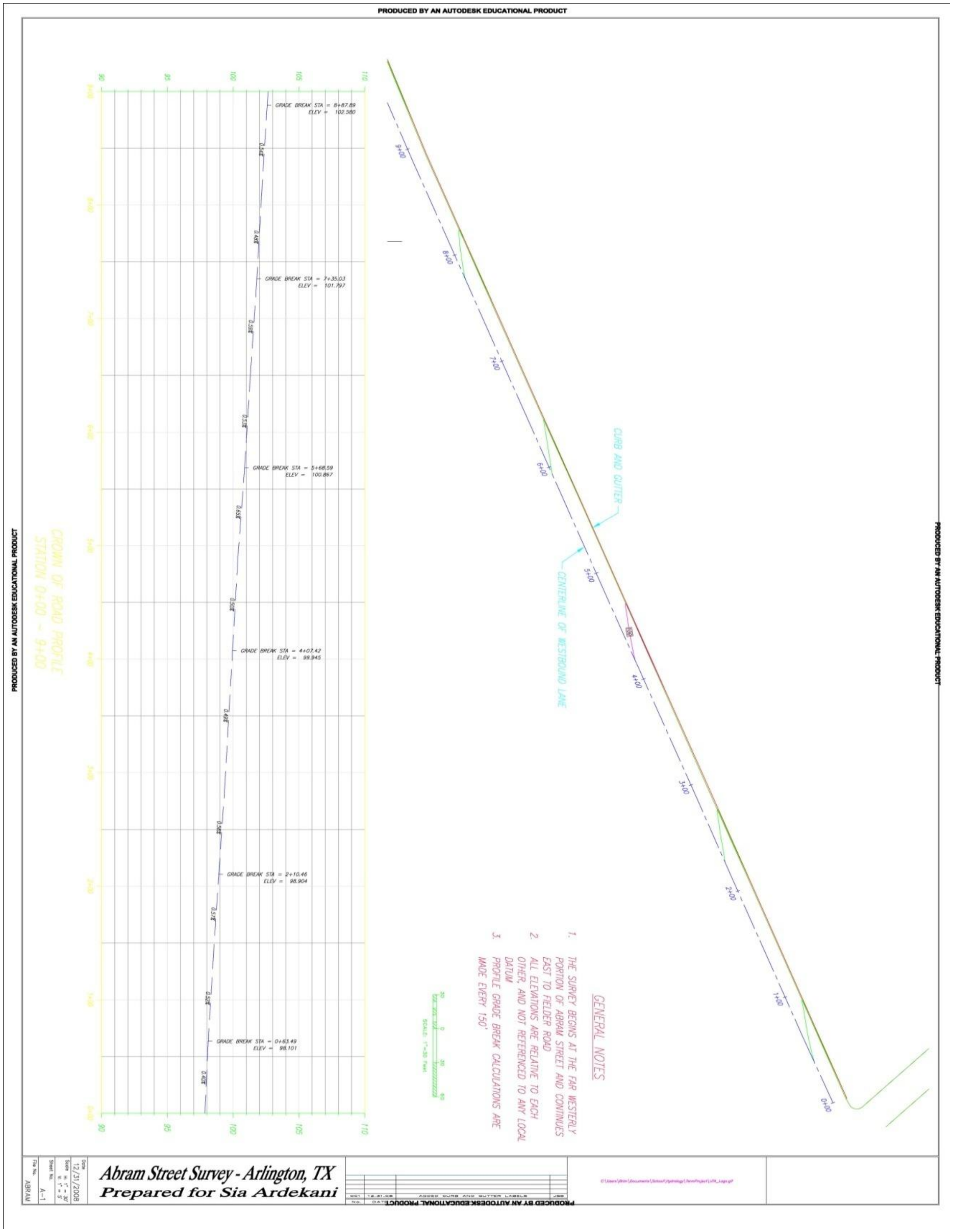


Exhibit B-3 Longitudinal Grade for Abram Street (PCC) in Arlington, TX (Part 1).

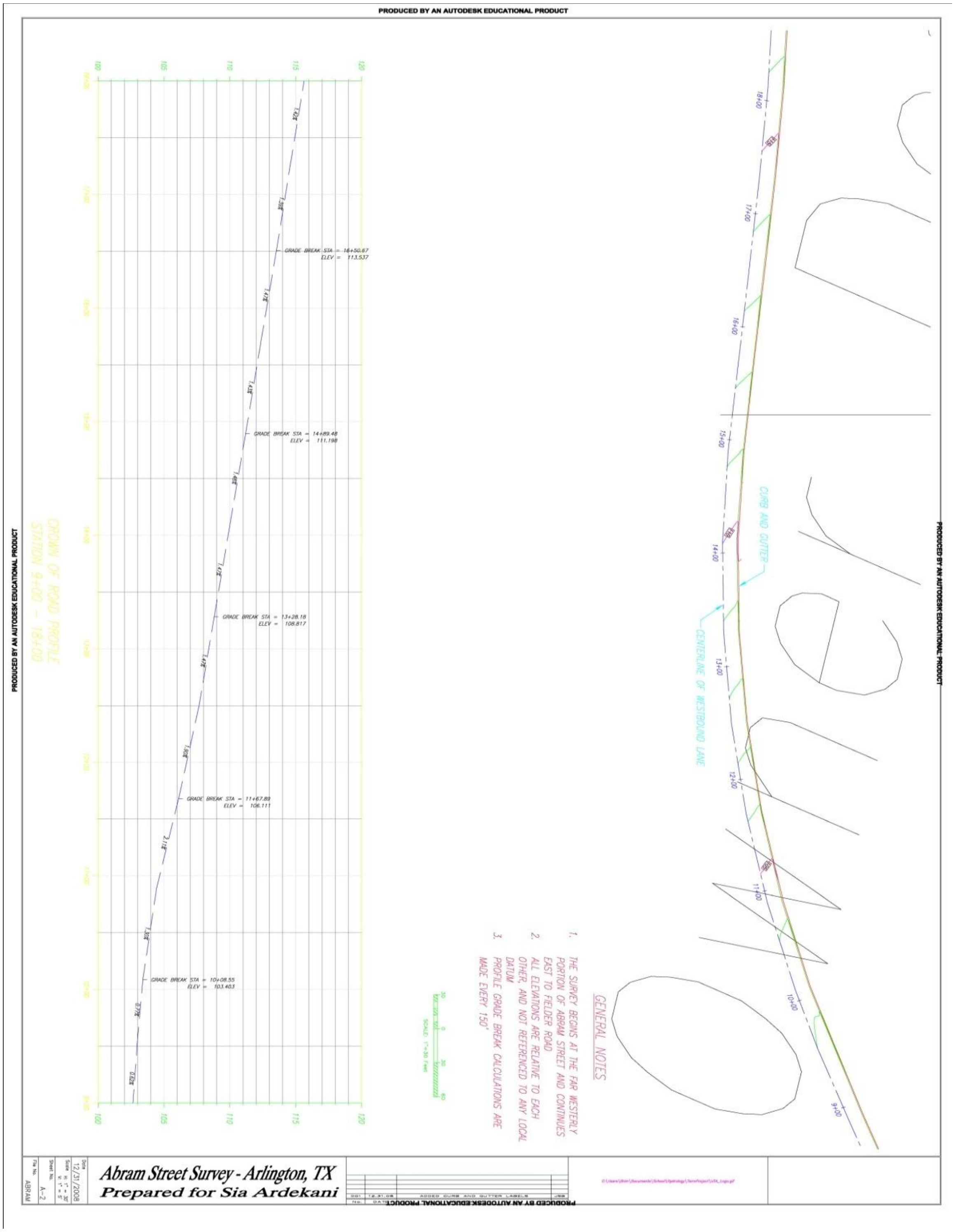


Exhibit B-4 Longitudinal Grade for Abram Street (PCC) in Arlington, TX (Part 2).

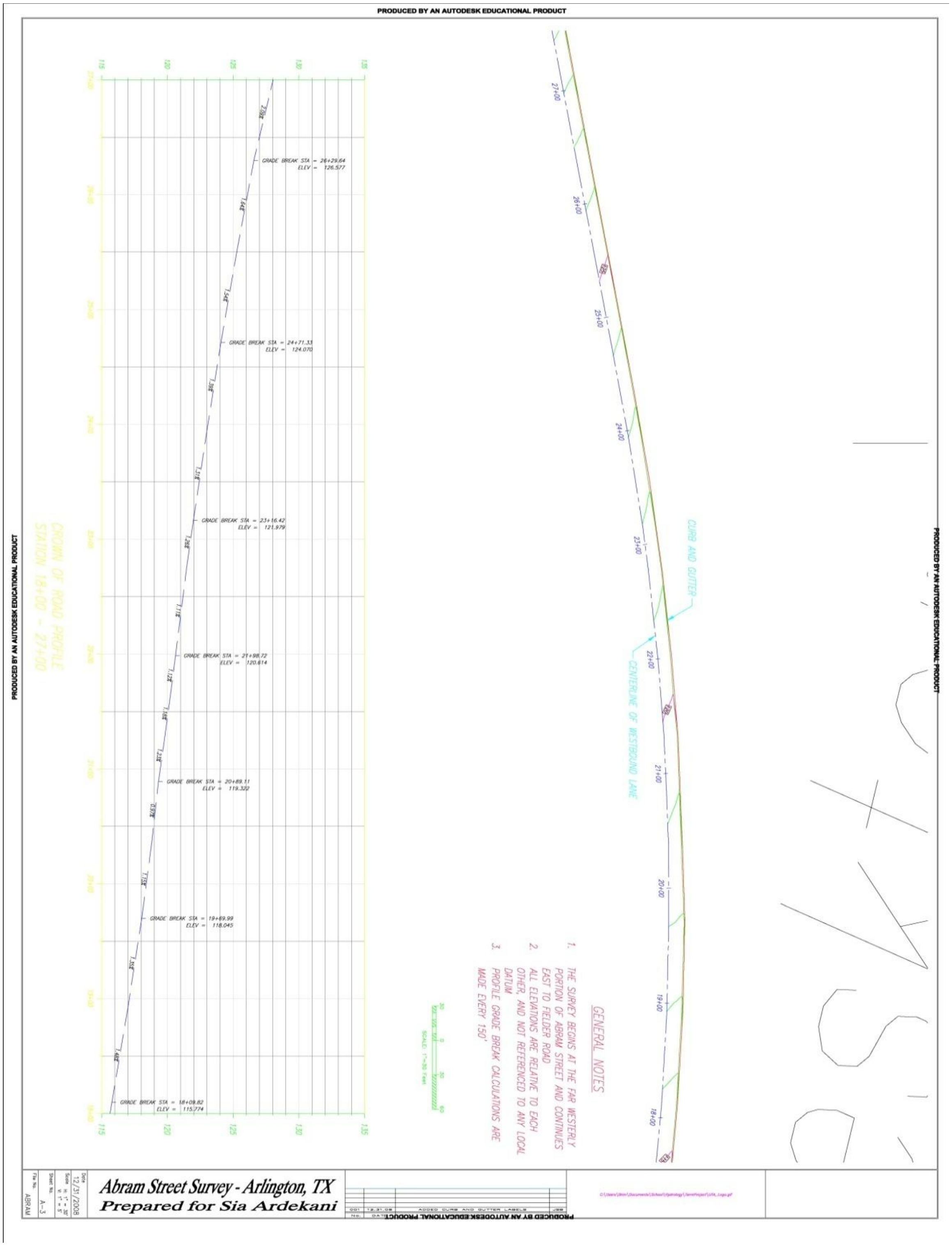


Exhibit B-5 Longitudinal Grade for Abram Street (PCC) in Arlington, TX (Part 3).

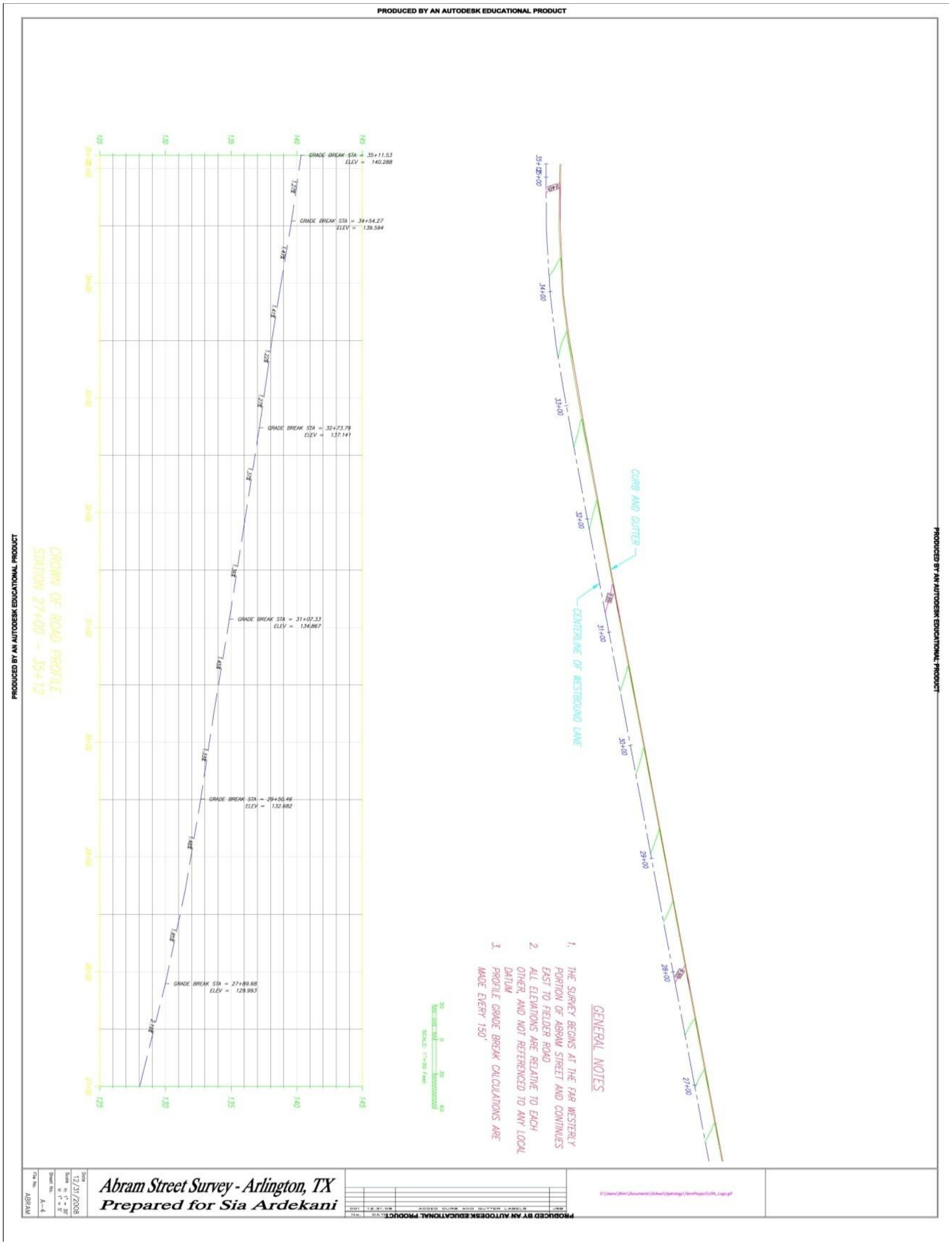
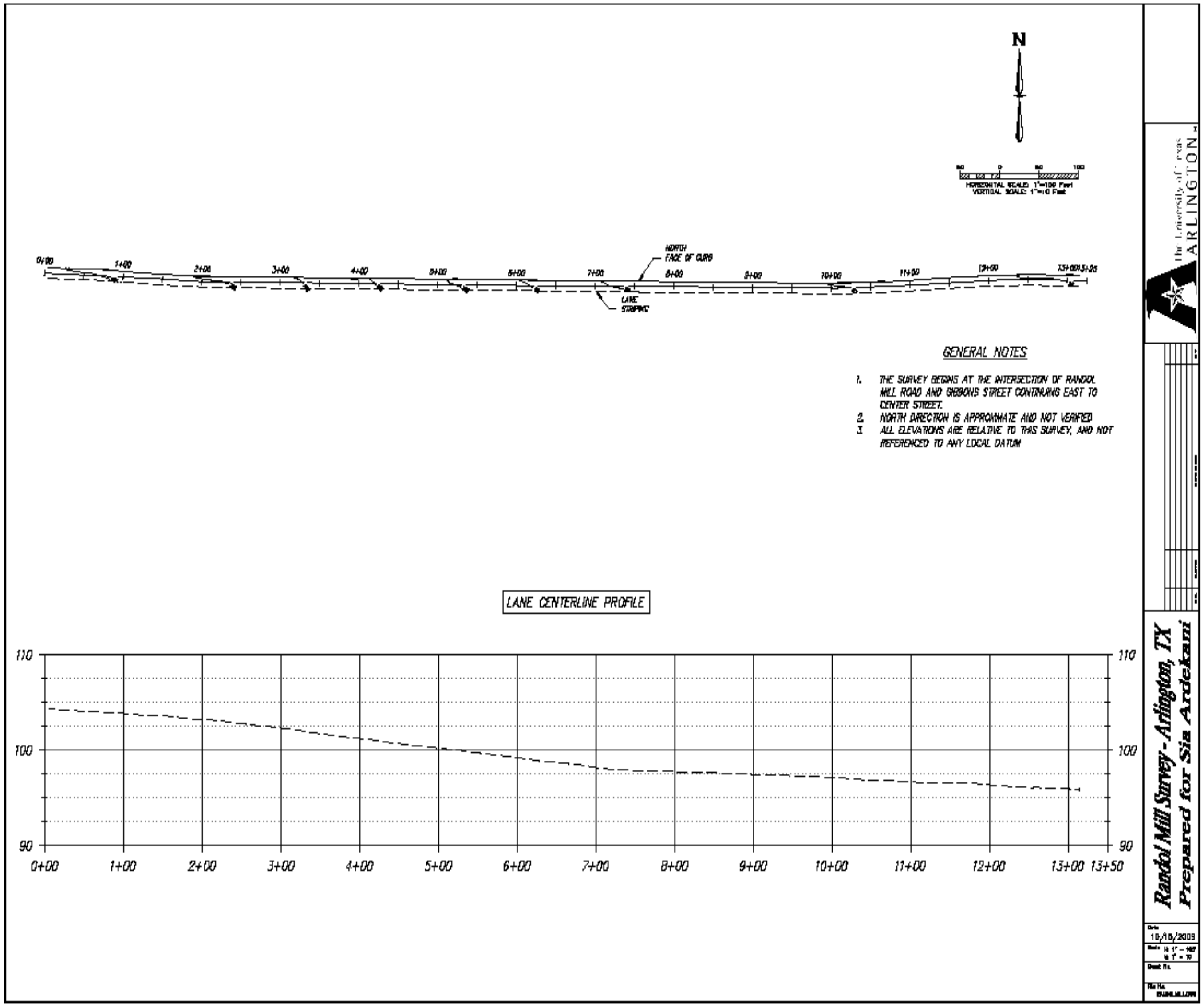


Exhibit B-6 Longitudinal Grade for Abram Street (PCC) in Arlington, TX (Part 4).



GENERAL NOTES

1. THE SURVEY BEGINS AT THE INTERSECTION OF RANDOL MILL ROAD AND GIBBONS STREET CONTINUING EAST TO CENTER STREET.
2. NORTH DIRECTION IS APPROXIMATE AND NOT VERIFIED
3. ALL ELEVATIONS ARE RELATIVE TO THIS SURVEY, AND NOT REFERENCED TO ANY LOCAL DATUM

Exhibit B-7 Longitudinal Grade for Randol Mill Road (AC) in Arlington, TX.

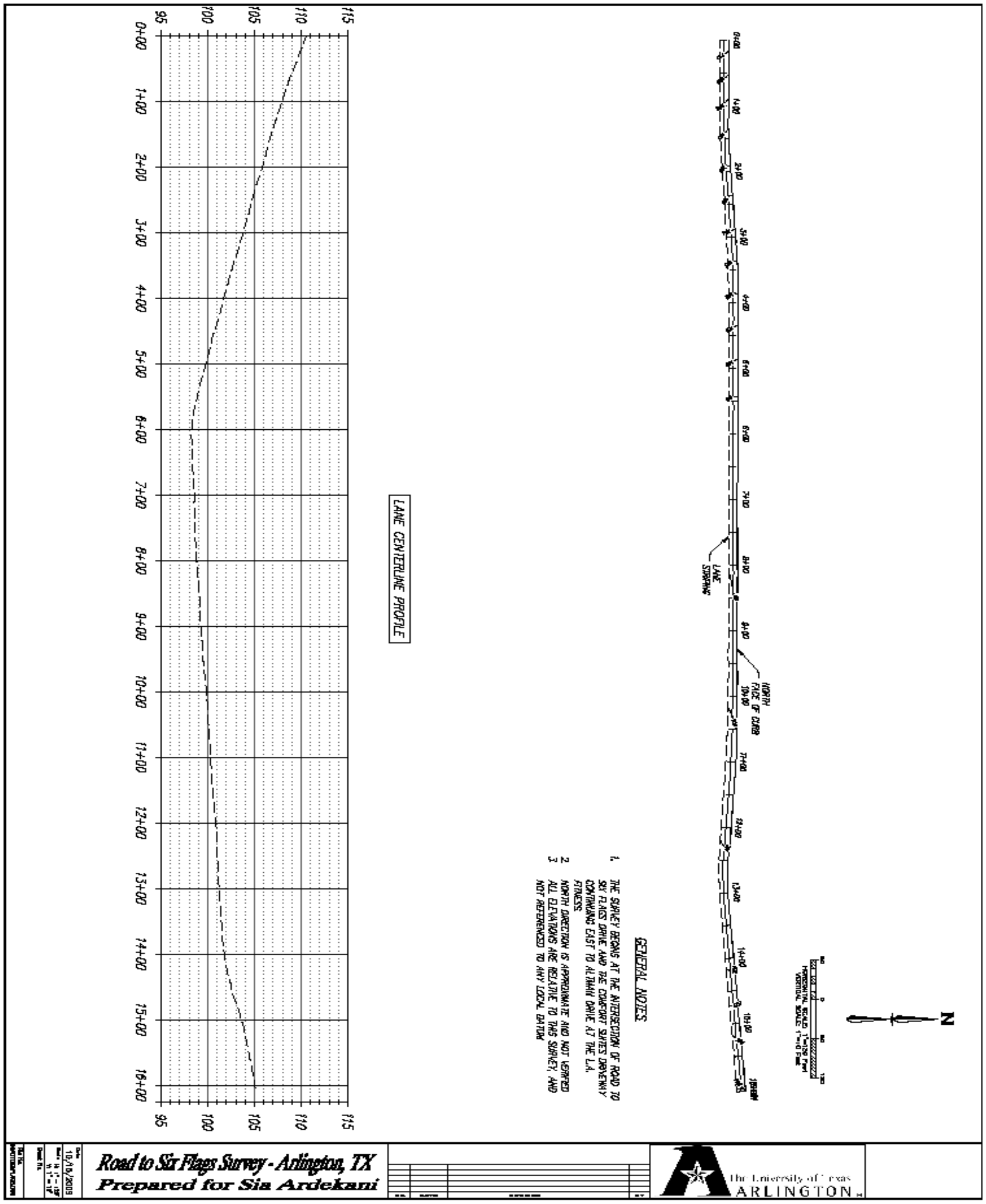


Exhibit B-8 Longitudinal Grade for Road to Six Flags Street (PCC) in Arlington, TX.

APPENDIX C

FUEL MEASUREMENT RAW DATA

Study Date	Temp. (ºF)	Humidity (%)	Wind Speed (mph) /direction	Road Sites	No.	Fuel Consumed (10^{-3} GPM)	Average Fuel Consumption (10^{-3} GPM)
November 7, 2008 Approx. time: 2pm	69	30	7 W	Pecandale	1	46.2	43.7
					2	42.6	
					3	42.2	
				Abram	1	39.3	39.8
					2	41.0	
					3	39.1	
January 16, 2009 Approx. time: 4pm	44	48	7 S	Pecandale	1	54.2	53.2
					2	52.9	
					3	52.6	
				Abram	1	46.8	46.8
					2	42.0	
					3	51.6	
April 21, 2011 Approx. time: 5pm	85	53	15 S	Pecandale	1	53.7	54.1
					2	55.0	
					3	53.6	
				Abram	1	48.4	51.3
					2	52.5	
					3	53.0	
April 23, 2011 Approx. time: 3pm	85	55	17 S	Pecandale	1	51.7	52.6
					2	52.8	
					3	53.3	
				Abram	1	50.0	48.7
					2	48.2	
					3	47.9	
April 28, 2011 Approx. time: 10am	64	35	3 N	Pecandale	1	52.8	53.8
					2	55.7	
					3	53.0	
				Abram	1	47.6	49.7
					2	49.8	
					3	51.8	
May 3, 2011 Approx. time: 2pm	65	43	5 N	Pecandale	1	58.8	58.6
					2	59.1	
					3	58.0	
				Abram	1	54.0	53.4
					2	53.0	
					3	53.2	
May 5, 2011 Approx. time: 2pm	76	37	15 S	Pecandale	1	56.3	55.1
					2	53.9	
					3	55.1	
				Abram	1	53.0	51.0
					2	49.4	
					3	50.7	

Exhibit C-1 Fuel Measurement of Pecandale (AC) vs. Abram (PCC) at Constant Speed of 30 mph.

Study Date	Temp. (ºF)	Humidity (%)	Wind Speed (mph) /direction	Road Sites	No.	Fuel Consumed (10^{-3} GPM)	Average Fuel Consumption (10^{-3} GPM)
November 7, 2008 Approx. time: 2pm	69	30	7 W	Pecandale	1	236.2	239.0
					2	240.6	
					3	240.2	
				Abram	1	240.2	232.5
					2	229.6	
					3	227.8	
January 16, 2009 Approx. time: 4pm	44	48	7 S	Pecandale	1	269.0	260.5
					2	243.8	
					3	268.6	
				Abram	1	236.8	234.6
					2	220.2	
					3	246.7	
April 21, 2011 Approx. time: 5pm	85	53	15 S	Pecandale	1	265.6	281.0
					2	270.1	
					3	307.2	
				Abram	1	239.6	257.7
					2	245.9	
					3	287.5	
April 23, 2011 Approx. time: 3pm	85	55	17 S	Pecandale	1	270.1	293.6
					2	304.9	
					3	305.7	
				Abram	1	276.9	271.6
					2	269.4	
					3	268.6	
April 28, 2011 Approx. time: 10am	64	35	3 N	Pecandale	1	280.7	281.5
					2	285.3	
					3	278.5	
				Abram	1	278.5	273.7
					2	276.9	
					3	265.6	
May 3, 2011 Approx. time: 2pm	65	43	5 N	Pecandale	1	267.1	273.2
					2	280.0	
					3	272.4	
				Abram	1	286.8	290.6
					2	283.7	
					3	301.2	
May 5, 2011 Approx. time: 2pm	76	37	15 S	Pecandale	1	276.2	274.2
					2	258.0	
					3	288.3	
				Abram	1	270.3	271.9
					2	262.6	
					3	283.0	

Exhibit C-2 Fuel Measurement of Pecandale (AC) vs. Abram (PCC) at Acceleration of 3 mph/second.

Study Date	Temp. (ºF)	Humidity (%)	Wind Speed (mph) /direction	Road Sites	No.	Fuel Consumed (10^{-3} GPM)	Average Fuel Consumption (10^{-3} GPM)
July 3, 2009 Approx. time: 8am	81	58	6 S	Randol Mill	1	45.3	47.7
					2	48.0	
					3	49.7	
				Six Flags	1	39.8	41.1
					2	42.1	
					3	41.2	
July 23, 2009 Approx. time: 8am	77	60	3 N	Randol Mill	1	51.5	52.8
					2	55.5	
					3	51.5	
				Six Flags	1	46.6	45.4
					2	46.9	
					3	42.7	
July 24, 2009 Approx. time: 8am	78	71	0	Randol Mill	1	52.8	51.7
					2	52.2	
					3	50.1	
				Six Flags	1	46.5	42.1
					2	41.3	
					3	38.5	
April 21, 2011 Approx. time: 5pm	85	53	15 S	Randol Mill	1	48.8	47.8
					2	47.7	
					3	47.0	
				Six Flags	1	37.0	42.0
					2	46.1	
					3	42.8	
April 23, 2011 Approx. time: 3pm	85	55	17 S	Randol Mill	1	51.5	48.9
					2	45.6	
					3	49.7	
				Six Flags	1	37.8	39.7
					2	41.8	
					3	39.6	
April 28, 2011 Approx. time: 10am	64	35	3 N	Randol Mill	1	48.0	49.3
					2	48.6	
					3	51.5	
				Six Flags	1	36.7	42.3
					2	44.6	
					3	45.5	
May 3, 2011 Approx. time: 2pm	65	43	5 N	Randol Mill	1	48.1	47.2
					2	45.6	
					3	47.8	
				Six Flags	1	41.8	42.0
					2	42.3	
					3	41.9	

Exhibit C-3 Fuel Measurement of Randol Mill (AC) vs. Road to Six Flags (PCC) at Constant Speed of 30 mph.

Study Date	Temp. (ºF)	Humidity (%)	Wind Speed (mph) /direction	Road Sites	No.	Fuel Consumed (10^{-3} GPM)	Average Fuel Consumption (10^{-3} GPM)
July 3, 2009 Approx. time: 8am	81	58	6 S	Randol Mill	1	257.3	256.5
					2	254.2	
					3	258.0	
				Six Flags	1	224.0	243.3
					2	248.9	
					3	257.1	
July 23, 2009 Approx. time: 8am	77	60	3 N	Randol Mill	1	288.3	266.1
					2	248.2	
					3	261.8	
				Six Flags	1	231.5	235.1
					2	239.9	
					3	233.8	
July 24, 2009 Approx. time: 8am	78	71	0	Randol Mill	1	252.0	252.7
					2	261.8	
					3	244.4	
				Six Flags	1	235.3	240.1
					2	250.5	
					3	234.4	
April 21, 2011 Approx. time: 5pm	85	53	15 S	Randol Mill	1	294.3	262.6
					2	258.8	
					3	234.6	
				Six Flags	1	236.1	228.8
					2	218.7	
					3	231.5	
April 23, 2011 Approx. time: 3pm	85	55	17 S	Randol Mill	1	272.4	278.2
					2	268.6	
					3	293.6	
				Six Flags	1	237.6	258.0
					2	266.3	
					3	270.1	
April 28, 2011 Approx. time: 10am	64	35	3 N	Randol Mill	1	274.7	271.6
					2	268.6	
					3	271.6	
				Six Flags	1	230.0	231.0
					2	230.0	
					3	233.1	
May 3, 2011 Approx. time: 2pm	65	43	5 N	Randol Mill	1	245.9	256.3
					2	264.1	
					3	258.8	
				Six Flags	1	242.1	236.8
					2	230.8	
					3	237.6	

Exhibit C-4 Fuel Measurement of Randol Mill (AC) vs. Road to Six Flags (PCC) at Acceleration of 3 mph/second.

REFERENCES

1. An, F., Friedman, D., and Ross, M. (2002). "Near-Term Fuel Economy Potential for Light-Duty Trucks." *SEA Technical Paper*, 2002-01-1900.
2. Archondo-Callao, R. S., and Faiz, A. (1994). "Estimating Vehicle Operating Costs." *World Bank Technical Paper*(234).
3. Bein, P., and Biggs, D. C. (1993). "Critique of Texas Research and Development Foundation on Vehicle Operating Cost Model." *Transportation Research Record*(1395), 114-121.
4. Brown, A. (2009). "Carbon Footprint of HMA and PCC Pavements." *International Conference on Perpetual Pavements*.
5. California Energy Commission. (2003). "California State Fuel-Efficient Tire Report: Volume I." *600-03-001F*.
6. Casadei, A., and Broda, R. (2008). "Impact of Vehicle Weight Reduction on Fuel Economy for Various Vehicle Architectures." *FB769 RD.07/71602.2*, Ricardo Inc.
7. Chang, M. F., Evans, L., Herman, R., and Wasielewski, P. (1976). "The Influence of Vehicle Characteristics, Driver Behavior, and Ambient Temperature on Gasoline Consumption in Urban Traffic." *Transportation Research Record*(599), 25-30.
8. Christie, T. (2011). "Research Report Points out Road to Energy Savings." Texas Asphalt, 30.

9. City of Arlington. (2011). "Traffic Count Maps." <http://www.arlingtontx.gov/publicworks/pdf/2010_Traffic_Counts.pdf> (November, 2011).

10. Delatte, N. (2008). *Concrete Pavement Design, Construction and Performance*, Taylor & Francis.

11. EcoBusinessLinks. (2009). "The Carbon Emissions Offset Directory." <http://www.ecobusinesslinks.com/carbon_offset_wind_credits_carbon_reduction.htm> (May, 2009).

12. Energy and Environmental Analysis Inc. (2001). "Owner Related Fuel Economy Improvements." Arlington, VA.

13. Evans, L., Herman, R., and Lam, T. (1976a). "Gasoline Consumption in Urban Traffic." *SAE Technical Paper*, 760048.

14. Evans, L., Herman, R., and Lam, T. (1976b). "Multivariate Analysis of Traffic Factors Related to Fuel Consumption in Urban Driving." *Transportation Science*, 10(2), 205.

15. Federal Highway Administration. (2011). "FHWA Vehicle Types." <http://www.fhwa.dot.gov/policy/ohpi/vehclass.htm> (May, 2011).

16. Goodyear. (2008). "Factors Affecting Truck Fuel Economy." <http://www.goodyear.com/truck/pdf/radialretserv/Retread_S9_V.pdf> (June, 2008).

17. Huang, Y. H. (2004). *Pavement Analysis and Design*, Pearson Prentice Hall, Upper Saddle River, NJ.

18. Jonsson, P., and Hultqvist, B.-Å. (2009). "Measurement of Fuel Consumption on Asphalt and Concrete Pavements North of Uppsala." Swedish National Road and Transport Research Institute, Linköping, Sweden.

19. Kutner, M. H., Nachtsheim, C. J., Neter, J., and Li, W. (2005). *Applied Linear Statistical Models*, McGraw-Hill.

20. Larson, T. (1992). *The Bridge*, 22(1).

21. Lubrizol. (2011). "Passenger Car Market Overview." <http://www.lubrizol.com/EuropeanEngineOils/PCMarketVideo.html> (March, 2011).

22. Nair, H. S., and Bhat, C. R. (2000). "Modeling Trip Duration for Mobile Source Emissions Forecasting." *FHWA/TX-0-1838-7*, Center for Transportation Research, the University of Texas at Austin.

23. North Central Texas Council of Government. (2007). "Transportation Conformity Determination for the Mobility 2030: The Metropolitan Transportation Plan and 2006-2008 Transportation Improvement Program as Amended." <http://www.nctcog.org/trans/air/conformity/ConformityDeterminations.asp> (April, 2009).

24. Ozbay, K., Parker, N. A., Jawad, D., and Hussain, S. (2003). "Guidelines for Life Cycle Cost Analysis." *FHWA-NJ-2003-012*, Federal Highway Administration.

25. Pagerit, S., Sharer, P., and Rousseau, A. (2006). "Fuel Economy Sensitivity to Vehicle Mass for Advanced Vehicle Powertrains." *Society of Automotive Engineers*, 2006-01-0665.

26. Papagiannakis, A. T. (1999b). "On the Relationship between Truck Operating Costs and Pavement Roughness." *SAE Technical Paper*, 1999-01-3783.

27. Papagiannakis, A. T., and Delwar, M. (1999a). "Methodology to Improve Pavement Investment Decisions." Transportation Research Board, Washington, D.C.

28. Papagiannakis, A. T., and Delwar, M. "Incorporating User Costs into Pavement Management Decisions." *Proceedings of the Fifth International Conference on Managing Pavements*, Seattle, Washington.

29. Peterson, D. E. (1985). "Life-Cycle Cost Analysis of Pavements." *National Cooperative Highway Research Program*.

30. Sayers, M. W., and Karamihas, S. M. (1998). "The Little Book of Profiling." <http://www.umtri.umich.edu/content/LittleBook98R.pdf> (November, 2009).

31. Shell. (2011). "Shell concept lubricant achieves 6.5% fuel economy benefit." <http://www.shell.com/home/content/lubes/media_centre/news_media_releases/2011/shell_concept_lubricant.html> (February, 2011).

32. Sovran, G., and Bohn, M. (1981). "Formulae for Tractive Energy Requirements for Vehicles Driving the EPA Schedule." *SAE Technical Paper*, 810184.

33. Taylor, G. W., and Patten, J. D. (2006). "Effect of Pavement Structure on Vehicle Fuel Consumption – Phase III." *Technical Report CSTT-HVC-TR-068*, Portland Cement Association, Skokie, Illinois.

34. Texas Department of Transportation. (2004). *Standard Specifications for Construction and Maintenance of Highways, Streets, and Bridges*.

35. The Daily Green. (2009). "Low Rolling Resistance Tires Save Gas." <http://www.thedailygreen.com/living-green/blogs/cars-transportation/low-rolling-resistance-tires-461009> (December, 2010).

36. Thompson, G. (1979). "Fuel Economy Effects of Tires." *SDSB 79-13*, U.S. Environmental Protection Agency.

37. Transportation Energy Management Program. (1982). "A Technical Background Document for Automotive Fuel Economy." *DRS-82-01*, Ontario Ministry of Transportation and Communications.

38. TRB Special Report 285. (2006). "The Fuel Tax and Alternatives for Transportation Funding." Transportation Research Board, Washington, D.C.

39. TRB Special Report 286. (2006). "Tires and Passenger Fuel Economy." Transportation Research Board, Washington, D.C.

40. U.S. Bureau of Transportation Statistics. (2011). "Number of U.S. Aircraft, Vehicles, Vessels, and Other Conveyances." <http://www.bts.gov/publications/national_transportation_statistics/html/table_01_11.html> (January, 2011).

41. U.S. Department of Energy. (2008). "Annual Energy Review." <http://www.eia.gov/totalenergy/data/annual/> (June, 2008).

42. U.S. Department of Energy. (2010a). "Gas Mileage Tips." <http://www.fueleconomy.gov/feg/maintain.shtml> (October, 2010).

43. U.S. Department of Energy. (2010b). "Low Rolling Resistance Tires." <http://www.afdc.energy.gov/afdc/vehicles/fuel_economy_tires_light.html> (September, 2010).

44. U.S. Department of Energy. (2011). "Fuel Economy: Where the Energy Goes." <http://www.fueleconomy.gov/feg/atv.shtml> (January, 2011).

45. U.S. Environmental Protection Agency. (1980). "Passenger Car Fuel Economy, EPA and Road." *EPA 460/3-80-010*.

46. U.S. Environmental Protection Agency. (2000). "Emission Facts." *EPA420-F-00-013*.

47. U.S. Environmental Protection Agency. (2003). "User's Guide to MOBILE6.1 and MOBILE6.2." *EPA420-R-03-010*, Office of Transportation and Air Quality.

48. U.S. Environmental Protection Agency. (2005). "Emission Facts." *EPA420-F-05-001*.

49. U.S. Environmental Protection Agency. (2006). "Fuel Economy Labeling of Motor Vehicles: Revisions to Improve Calculation of Fuel Economy Estimates." *EPA420-D-06-002*.

50. VicRoads. (2008). "Moving Towards Carbon Neutral Road Construction - The Mickleham Road Project." <http://www.vicroads.vic.gov.au/Home/Moreinfoandservices/Environment/Greenhouse.htm> (October, 2008).

51. Walls, J., and Smith, M. R. (1998). "Life-Cycle Cost Analysis in Pavement Design – Interim Technical Bulletin." *FHWA-SA-98-079,* Office of Engineering, Pavement Division, Federal Highway Administration, Washington, D.C.
52. Washington State Department of Transportation. (2003). "Pavement Types." <http://training.ce.washington.edu/wsdot/Modules/02_pavement_types/02-6_body.htm> (April, 2011).
53. Wood, R. A., Downing, B. R., and Pearce, T. C. (1981). "Energy Consumption of an Electric, a Petrol and a Diesel Powered Light Goods Vehicles in Central London Traffic." *TRRL Report LR 1021*, Transport and Road Research Laboratory, Crowthorne, Berkshire.
54. Zaniewski, J. P. (1989). "Effect of Pavement Surface Type on Fuel Consumption." *SR289.01P*, Portland Cement Association, Skokie, Illinois.
55. Zaniewski, J. P., Butler, B. C., Cunningham, G., Elkins, G. E., Paggi, M. S., and Machemehl, R. (1982). "Vehicle Operating Costs, Fuel Consumption, and Pavement Type and Condition Factors." *DOT-FH-11-9678*, Federal Highway Administration, Washington, D.C.

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