Effect of Pavement Type on Fuel Consumption and Emissions

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ABSTRACT

The effect of pavement type on fuel consumption was investigated. Significant differences in fuel consumption and emissions rates were observed on rigid versus flexible pavement surfaces. The difference in rates could result in substantial differences in the total energy consumption and carbon footprints during the design life of roadway facilities and should be considered in life cycle cost analyses of alternative designs. Fuel consumption measurements were made on multiple runs by driving an instrumented van over two new pavement sections: a rigid and a flexible section of two parallel city streets. The two sections were both tangent sections with identical gradients and similar roughness. All other factors that could influence fuel consumption were either controlled or kept the same during the test runs. Two different driving modes were also performed: constant speed of 30 mph and acceleration from zero to 30 mph at a rate of 3 mph/second. All tests were conducted under dry pavement conditions with a four factor-level experimental design—two pavement types and two driving modes. The differences in fuel consumption rates were determined to be statistically significant at 10% level of significance for the constant speed runs with the rate for the rigid section being lower. Under the acceleration mode, while the rigid pavement runs again showed lower rates, the differences were not statistically significant. The total fuel consumption amounts were then used to estimate the total annual CO2 productions in the Dallas-Fort Worth region in Texas under each pavement surface type. Under similar urban driving conditions (30 mph), the rigid pavement results in a total fuel savings of about 177 million gallons and a reduction of approximately 0.62 million metric tons of CO2 per annum.

Key words: carbon footprints—cleanup cost—emissions—fuel consumption—fuel measurement
RESEARCH OBJECTIVES

The goal of this study is to investigate the effect of pavement type on fuel consumption and emissions. The study emphasis is on urban driving cycles at non-highway speeds, as more than half of the vehicular fuel consumption in the United States is due to urban driving. If significant differences in fuel consumption and emissions rates are observed across various pavement surface types, they may result in substantial differences in the total energy consumption and carbon footprints during the design life of roadway facilities. As such, those differences should be considered in life cycle cost analyses of alternative pavement designs.

The proposed study has entailed the use of an instrumented van to make fuel consumption measurements over two new pavement sections—a Portland cement concrete (PCC) and an asphalt concrete (AC) section. The two sections selected have similar geometric characteristics and differ only in the type of pavement. They are both tangent sections of two parallel collector streets in the city of Arlington, Texas, and have identical gradients and similar roughness. In the course of the fuel consumption measurements, every attempt is made to either control all other factors that could affect fuel consumption or keep the factors that cannot be controlled the same. These include vehicle weight, fuel tank level, tire pressure, ambient temperature, humidity, and wind speed and direction. Two different driving modes (constant speed and acceleration) are used in the test run measurements. For each run, in the cruise mode, the speed is kept at 30 mph, while in the acceleration mode, an acceleration of 3 mph/second is used. Tests are conducted under dry pavement condition. A four factor-level experimental design is utilized, including two pavement types (PCC vs. AC) and two driving modes (constant speed vs. acceleration). To obtain statistically meaningful results, six runs are made for each factorial combination, resulting in a total of 24 runs.

Given the millions of vehicle miles traveled (VMT) annually in major U.S. cities, even minute reductions in the fuel consumption rate per mile can be significant in the total fuel consumption and emissions savings during the design life of a project. To this end, as part of this study a procedure will be developed to quantify, given an estimate of the VMT and the vehicle mix, the total fuel consumption and carbon footprints over the design life of a pavement. Although the focus of the study is on city street urban driving where air quality concerns are paramount, the results could be easily extended to other classes of roadways.

LITERATURE REVIEW

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

The Elemental fuel consumption model developed by scientists at the General Motors (GM) research lab in Warren, Michigan, (Evans, Herman, and Lam 1976) was the widely accepted model among the fuel consumption models developed in the 1970s. This model showed that the fuel consumption in a vehicle varies greatly due to variables such as speed, acceleration-deceleration cycle, vehicle mass, and mechanical conditions of the vehicle such as tire pressure, wheel alignment, carburetion system, ambient conditions, and pavement surface conditions. The model speculated that about 75% 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 conditions.
condition and type. The fuel consumption differences due to rolling resistance were expected to be particularly significant for trucks and other heavy vehicles.

The most comprehensive study of the effect of pavements on fuel consumption was funded in the early 1980’s by the World Bank as part of the Highway Design Model development effort (Archondo-Callao and Faiz 1994). The life cycle cost in the Highway Design Model 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 costs contained the vehicle characteristics, such as engine size, speed, tire conditions, etc., and the road characteristics, such as smoothness and slope of the longitudinal profile. The smoothness and slope of the longitudinal profile became 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 (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.

Studies by Papagiannakis and Delwar (1999, 2001) resulted in a software program that highlighted the importance of incorporating vehicle operating costs in the life cycle cost analysis (LCCA) 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, the research by Zaniewski, Butler, Cunningham, Elkins, Paggi, and Machemehl (1982) and by Zaniewski (1989) has been the only effort to date to systematically assess the effect of pavement surface material type on fuel consumption. Their study 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. 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 LCCA of design alternatives for highway pavements. However, it is not readily clear whether and to what extent they are applicable to city streets, where urban carbon footprint is an increasingly important consideration in the analysis of design alternatives.

Vehicular fuel consumption and emissions are two crucial concerns in both transportation and environmental issues. Mobile sources generate VMT, and as they consume energy, they are the leading contributors to air pollution. According to the U.S. Bureau of Transportation Statistics (BTS), there were 250,851,833 registered vehicles in the United States in 2006. Approximately 93.5% of those vehicles were classified as passenger cars, SUVs, or single-unit trucks. Among three common fossil fuels—petroleum, natural gas, and coal—96% of the 2007 United States’ primary transportation energy consumption relied on petroleum or crude oil (Energy Information Administration, U.S. Department of Energy). This trend continues despite the oil price increases, which peaked at over $140 a barrel in June 2008. Gasoline, which is the main product from crude oil refining, is one of the major fuels consumed in the United States with a consumption level of over 142 billion gallons in 2007. The vehicular fuel consumption accounts for about half of this amount. As such, the transportation sector is the largest emitter of CO2 among energy-use sectors, such as industrial, residential, and commercial sectors. In motor vehicles, CO2 is the by-product of the combustion process released to the atmosphere as a tailpipe emission. It is one of the greenhouse gases that causes global warming. Between 1990 and 2007, the energy-related CO2 emission of the transportation sector grew 27.7% over the 17-year period and has grown by 1.4% per year since 1990 (Energy Information Administration, U.S. Department of Energy). As
a result, improving energy efficiency of the transportation sector, including improving vehicle shape, engine, tire tread, and roadway design, plays a vital role in reducing fuel consumption and exhaust gas emissions.

The current study sets out to systematically measure the influences of pavement surface type on fuel consumption with an emphasis on urban streets. Once these influences are quantified, a secondary objective is to estimate the associated carbon footprint and cleanup costs in analyzing the life cycle cost of city street pavement alternatives.

EXPERIMENTAL DESIGN AND DATA COLLECTION

In achieving the research objectives, fuel consumption measurements are made using an instrumented vehicle driven over two types of pavement surfaces (PCC and AC) under two driving modes (constant speed and acceleration). In order to isolate the effect of pavement type on fuel consumption, attempts are made to either control or record all other key variables that might influence fuel consumption. These include vehicle weight, tire pressure, wind speed and direction, ambient temperature, atmospheric pressure, humidity, elevation, roadway gradient and curvature, and surface roughness.

The tests are performed using an instrumented vehicle equipped with an onboard data acquisition system. The fuel sensor, the temperature sensors, and the data acquisition system (Figure 1) are hooked up to the engine as schematically shown in Figure 2. Two fuel sensors measure instantaneously the amount of fuel entering the engine and returned to the tank. The temperatures of the fuel entering the engine and returning to the tank are also measured using two temperature gauges. In addition to the fuel amounts and fuel temperatures, the data acquisition system also records the instantaneous vehicle speed.
Figure 1. On-board instruments

(a) Fuel meter  
(b) Temperature gauge  
(c) Data acquisition system

Figure 2. Schematic diagram of the sensor and the data acquisition system
Two types of city street sections, a PCC versus an AC, have been selected. Except for the surface material, the two sections have similar gradients, curvature, age, and roughness rating. The PCC section selected for this research is the Abram Street located in Arlington, Texas. The AC test section is the Pecandale Drive, also located in Arlington, Texas. The two sections run parallel and are two city blocks apart. The Texas Department of Transportation made roughness measurements for these sections resulting in International Roughness Index (IRI) measurements of 174.6 in/mile for the PCC and 180.6 in/mile for the AC section. These IRI values are only 3% different and are both in the IRI range for new pavements. Regarding the profile of the two road sections, a survey was performed. It was determined that the average longitudinal gradient for the two sections was identical at +1.2% in the eastbound direction (direction of observations).

The variables recorded for each measurement run included the following:

- Date
- Time
- Ambient air temperature
- Atmospheric pressure
- Humidity
- Wind speed/direction
- Temperature of fuel flowing into/out of the tank
- Vehicle weight
- Tire pressure
- Status of auxiliary devices (A/C, Radio, Headlights, Windows)

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 experimental factors and levels are also shown in Table 1. The two levels and two factors are varied together, yielding four treatment combinations or responses as shown in Table 2. Table 3 shows the two-level, two-factor experimental design.

### Table 1. The experimental factors and levels

<table>
<thead>
<tr>
<th>Factor</th>
<th>Description</th>
<th>Level A</th>
<th>Level B</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Pavement Type</td>
<td>PCC</td>
<td>AC</td>
</tr>
<tr>
<td>II</td>
<td>Driving Mode</td>
<td>Constant Speed*</td>
<td>Acceleration**</td>
</tr>
</tbody>
</table>

*Speed is kept constant at 30 mph during the data collection run.

**Data are collected during accelerating from zero to 30 mph at a rate of 3 mph/sec.

### Table 2. The four factor-level combinations

<table>
<thead>
<tr>
<th>Factor-Level Combination</th>
<th>Pavement Type</th>
<th>Driving Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>PCC</td>
<td>Constant Speed</td>
</tr>
<tr>
<td>2</td>
<td>PCC</td>
<td>Acceleration</td>
</tr>
<tr>
<td>3</td>
<td>AC</td>
<td>Constant Speed</td>
</tr>
<tr>
<td>4</td>
<td>AC</td>
<td>Acceleration</td>
</tr>
<tr>
<td>Run</td>
<td>Description</td>
<td></td>
</tr>
<tr>
<td>-----</td>
<td>------------------------</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>PCC, Constant Speed</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>PCC, Acceleration</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>AC, Constant Speed</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>AC, Acceleration</td>
<td></td>
</tr>
</tbody>
</table>

A number of observational repeat tests are necessary for each run of the above table in order to be able to draw statistically significant conclusions. It is expected that six observational repeat tests in each run will be sufficient to yield a 90% level of confidence with a ±10% error, although this also depends on data variance and tolerable level of error. If larger than expected variability is observed from one run to the next as experimental runs are made, the number of repeat tests may have to be increased.

RESULTS

The fuel consumption measurements for dry pavement condition were performed in November 2008. Four sets of factors measured were as follows:

- PCC, Constant Speed
- PCC, Acceleration
- AC, Constant Speed
- AC, Acceleration

The fuel flow rate in gallons per minute and the cumulative fuel consumed in each scenario were retrieved from the onboard data acquisition system. Two examples of the raw data plot are shown in Figure 3 for PCC at constant speed and in Figure 4 for PCC under the acceleration driving mode.
Table 4 summarizes the average fuel consumption rate for each of the four dry pavement and driving mode runs. In the constant speed mode (Figure 3), a cruise speed of 30 mph was maintained throughout
the test section. Under the acceleration driving mode (Figure 4), the fuel data were collected while accelerating from zero to 30 mph in 10 seconds, yielding an average acceleration rate of 3 mph/second. For each driving mode, the total fuel consumed was recorded, and the corresponding consumption rate in gallons per mile was computed.

### Table 4. Average fuel consumption rates for PCC versus AC sections

<table>
<thead>
<tr>
<th>Average Fuel Consumption (10⁻³ gals/mile)</th>
<th>Test Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCC, Constant Speed</td>
<td>Date: November 7, 2008&lt;br&gt;Temperature: 69 °F&lt;br&gt;Pressure: 30.08 in. Hg&lt;br&gt;Wind: 7 mph W (tailwind)&lt;br&gt;Engine: Warm&lt;br&gt;Tire Pressure: 50 psi&lt;br&gt;Tank Level: Full&lt;br&gt;IRI (in./mi): 174.6 (PCC), 180.6 (AC)&lt;br&gt;Longitudinal Slope: +1.2% (PCC), +1.2% (AC)</td>
</tr>
<tr>
<td>AC, Constant Speed</td>
<td></td>
</tr>
<tr>
<td>PCC, Acceleration</td>
<td></td>
</tr>
<tr>
<td>AC, Acceleration</td>
<td></td>
</tr>
</tbody>
</table>

In both driving modes, the fuel consumption rate for the PCC pavement was observed to be lower than the rate for the AC pavement. These observed differences in fuel consumption rates were, however, tested for statistical significance at 10% level of significance. One-sided t-tests were conducted to probe whether the fuel rates on the PCC section were statistically lower than the rates on the AC section. It was determined that in the constant speed mode, the lower fuel consumption rate on the PCC section was in fact statistically significant at 10% level of significance. However, this was not the case under the acceleration mode. Therefore, it can be concluded that under constant travel speed of 30 mph, the PCC section results in statistically lower fuel consumption rate than the AC section. Under an acceleration of 3 mph/sec, while the PCC still resulted in a slightly lower consumption rate, the difference in consumption rate was found not to be statistically significant.

Under the constant speed scenario, the fuel rates were applied to the annual VMT in the Dallas-Fort Worth (DFW) region of Texas. The total annual VMT in the nine-county DFW region is estimated to be 62,697 million miles per year. The fuel consumption rates were applied to this VMT to obtain total annual fuel consumption estimates for a hypothetical mix of vehicles as shown in Table 5 (for PCC) and Table 6 (for AC). The CO₂ emissions in the PCC case were estimated using the following empirically derived regression model (Afotey 2008):

\[
CO_2 \text{ amount in grams/sec} = 0.867 + 0.011 \ V + 1.172 \ a + 0.208 \ aV,
\]

where \( V \) is the velocity in mph and \( a \) is the acceleration rate in mph/second. The CO₂ emissions for all other cases were estimated as a ratio of the fuel consumption rate for each respective case relative to the field-measured rate for the PCC section.
Table 5. Calculations of annual fuel consumption and CO₂ emissions for the DFW region of Texas under dry PCC pavement and constant speed mode

<table>
<thead>
<tr>
<th>Average Vehicle Mass (lbs)</th>
<th>% in the mix</th>
<th>VMT (million miles/yr)</th>
<th>Fuel Rate (gals/mi)</th>
<th>Fuel Consumed (million gals/yr)</th>
<th>CO₂ Rate (grams/mi)</th>
<th>Total CO₂ (million metric tons/yr)</th>
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<tbody>
<tr>
<td>3,000</td>
<td>35</td>
<td>21,944</td>
<td>0.0407*</td>
<td>893.1</td>
<td>143.64</td>
<td>3.15</td>
</tr>
<tr>
<td>4,000</td>
<td>33</td>
<td>20,690</td>
<td>0.0543</td>
<td>1,122.8</td>
<td>191.52</td>
<td>3.96</td>
</tr>
<tr>
<td>5,000</td>
<td>14</td>
<td>8,778</td>
<td>0.0678</td>
<td>595.4</td>
<td>239.40</td>
<td>2.10</td>
</tr>
<tr>
<td>6,000</td>
<td>10</td>
<td>6,270</td>
<td>0.0814</td>
<td>510.4</td>
<td>287.28</td>
<td>1.80</td>
</tr>
<tr>
<td>7,000</td>
<td>8</td>
<td>5,016</td>
<td>0.0950</td>
<td>476.3</td>
<td>335.16</td>
<td>1.68</td>
</tr>
<tr>
<td>∑</td>
<td>100</td>
<td>62,697</td>
<td></td>
<td>3,598.0</td>
<td></td>
<td>12.70</td>
</tr>
</tbody>
</table>
*Measured in the field

Table 6. Calculations of annual fuel consumption and CO₂ emissions for the DFW region of Texas under dry AC pavement and constant speed mode

<table>
<thead>
<tr>
<th>Average Vehicle Mass (lbs)</th>
<th>% in the mix</th>
<th>VMT (million miles/yr)</th>
<th>Fuel Rate (gals/mi)</th>
<th>Fuel Consumed (million gals/yr)</th>
<th>CO₂ Rate (grams/mi)</th>
<th>Total CO₂ (million metric tons/yr)</th>
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<tbody>
<tr>
<td>3,000</td>
<td>35</td>
<td>21,944</td>
<td>0.0427*</td>
<td>937.0</td>
<td>143.64</td>
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<td>5,000</td>
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<td>0.0712</td>
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<td>13.32</td>
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</tbody>
</table>
*Measured in the field

The field-measured fuel rates under the constant speed mode in Tables 5 and 6 represented a 3,000 lb vehicle (the instrumented test vehicle). 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 mass ratio of the two respective classes. For example, a 6,000 lb vehicle was estimated to have twice as large a fuel consumption rate than the 3,000 lb test vehicle. The total fuel consumption amounts per annum then were estimated using those rates and the total vehicle miles of travel for each vehicle class.

The overall results for the constant speed mode are summarized in Table 7. In Table 7, if the annual vehicle miles of travel in the DFW region took place at a constant speed of 30 mph on PCC pavements, the statistically lower fuel rate could result in an annual fuel savings of 177 million gallons and an annual CO₂ reduction of about 0.62 million metric tons. Assuming an average fuel cost of about $2/gallon and an average CO₂ cleanup cost of about $18/metric (Eco Business Links 2009), these differences would amount to a fuel and cleanup cost savings in the DFW region of approximately $354 million and $11 million per year, respectively. These cost savings should possibly be considered in the LCCA of alternative city street pavement projects.
Table 7. Total annual fuel consumption and CO₂ emissions for the DFW region of Texas under each pavement type

<table>
<thead>
<tr>
<th>Pavement Type</th>
<th>Fuel Consumed (million gals/yr)</th>
<th>Total CO₂ (million metric tons/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCC, Constant Speed (30 mph)</td>
<td>3,598</td>
<td>12.70</td>
</tr>
<tr>
<td>AC, Constant Speed (30 mph)</td>
<td>3,775</td>
<td>13.32</td>
</tr>
</tbody>
</table>

CONCLUSIONS

Under dry surface conditions at urban driving speed of 30 mph, fuel consumption per unit distance is lower on concrete pavement than on asphalt pavement. Moreover, the observed difference in fuel consumption rate is statistically significant at 10% level of significance with the rate for the concrete pavement being lower. The potential savings in fuel consumed and CO₂ emissions over the life of the project could be substantial and should be considered in the life cycle cost analysis of alternative projects and in sustainable development considerations such as the carbon footprint of a roadway project.
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