Effects of Pavement Structure on Vehicle Fuel Consumption

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ABSTRACT

A highway tractor with a van semi-trailer and a passenger car were driven over concrete, asphalt and composite (asphalt over concrete) paved roads to detect if fuel savings could be attributed to any of the three pavement surfaces. The tests were conducted in winter, spring, summer night, summer day and fall weather conditions and at two road speeds: 60 km/h and 100 km/h. Additionally, the trailer was loaded to three different weights to establish if loading was a contributing factor to fuel consumption differences among pavement types. All testing was performed on open highways in Ontario and Quebec. The acquired data were then analysed using multiple regression which formed the basis for a set of predictive mathematical models. A number of conclusions regarding the relationship between pavement type and fuel efficiency were drawn from these models. For the purposes of this presentation, the passenger car component has been ignored.

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1 INTRODUCTION

The Centre for Surface Transportation Technology (CSTT) at NRC was tasked jointly by The Cement Association of Canada (CAC) and Natural Resources Canada (NRCan) Action Plan 2000 on Climate Change (Minerals and Metals Programme) to perform a third phase of testing to investigate the effects of pavement structure on fuel consumption rate.

The third phase of testing was complementary to the previous two phases undertaken by CSTT/NRC [1], [2] of testing and employed many of the recommendations found in the Phase II rework final report (July 2002). Whereas previous studies used tractor and trailer combinations that were not as common to Canadian roads, this study utilized the most popular tractor and trailer combination currently found on Canadian roads: a tandem drive tractor pulling a van semi trailer.

1.1 Limitations

The roads used to quantify the fuel consumption differences were selected by the appropriate provincial authorities and, at the time of testing, were in good condition and represented current construction techniques and as such the study was not intended as a comparison between all grades of concrete or asphalt. Additionally, the resulting mathematical models were not designed to account for any localized transient effects such as variations in surface wear, concrete tining, surface friction or cross sectional pavement irregularities such as potholes, ruts or bumps. Variations in chemical or physical properties (e.g. elastomeric) of the pavements were also not considered.

2 PROCEDURE

The vehicle was tested in two loading conditions (empty and full), two speeds (60 km/h and 100 km/h) and during five different seasonal conditions. These variables are listed in Table 1.

Season	Ambient Temperature Range
Winter	< -10 °C
Spring	> - 5 °C and < +10 °C

Summer Day	> +29 °C
Summer Night	> +10 °C and < +25 °C
Fall	> - 5 °C and < +10 °C

Table 1- Summary of Temperature Ranges

Before testing began, a series of fuel consumption accuracy tests were performed. The OEM software was connected to the engine ECU and the level of fuel was accurately measured in all fuel tanks. The vehicle was then driven for a distance of several hundred kilometers and returned to CSTT. The depth of fuel in the tanks was then re-measured and compared against the data from the OEM logger. The results of these exercises produced an average difference of less than 0.2%.

For each loading and weather condition, the following test method was observed.

i. Tire pressures were recorded for all tires
ii. Air was added (or removed) from those tires found to be outside the test specification.
iii. The data acquisition system was connected to the inline adapter plug on the on-board Cummins engine management system.
iv. The test vehicle was driven to a test site at highway speed. All of the test sites were hundreds of kilometers from CSTT which allowed the powertrain, wheel bearings and tires to become sufficiently warm.
v. Several kilometers before the start of a test site, the data acquisition system was readied and zeroed, the tractor's cruise control was engaged at 100 km/h and the wind speed anemometer was erected in the vertical attitude. The use of cruise control minimized the effects of transient vehicular accelerations and decelerations as well as random or inconsistent inputs from the driver.
vi. As the tractor passed the established kilometer marker post, signifying the beginning of a test site, the data acquisition system was engaged and recording commenced.
vii. The tractor and trailer cruised over the test site in the right hand lane, minimizing steer input.
viii. Any deviations of more than 2 km/h from the desired speed constituted a failed test and steps (v) through (vii) were repeated until a steady state speed result was achieved.
ix. Steps (iv) through (viii) were repeated at 60 km/h.
x. The test team then ferried the vehicle to the next test site and repeated steps (iii) through (ix) until the completion of that 'test loop'.
xi. Steps (i) through (x) were then repeated on a separate day of testing in order to capture data at all the 'test loops'.
xii. All data were then saved for review and analysis. If a test run was determined to be outside of the pre-determined test limits (e.g. wind speed greater than 10 km/h), steps (i) through (ix) were repeated.

2.1 Tests and Surveys Performed by Third Party Contractors

Throughout the project, a variety of surveys were conducted by firms other than the CSTT/NRC. Each of the surveys provided critical static road data to complement the acquired fuel flow data used in the mathematical analysis. The surveys were as follows:

Precision GPS: A precision GPS survey was conducted to continuously define the road curvature and elevation/grade over the test sections. The sample rate was one measurement every second at a speed of 80 km/h. Since curvature and elevation do not vary by season, the GPS survey was conducted once, at the beginning of the project.

International Roughness Index (IRI): An IRI survey was conducted to define the roughness of the road surface over the test sections. The sample rate was one measurement every 50m for each wheel path and the units of measurement were m/km. It is well documented that IRI values can vary between seasons, therefore it was deemed essential to collect data seasonally. Each of the seasonal multiple regression models included only the IRI data collected for that season. [3]

Falling Weight Deflectometer (FWD): An FWD survey was conducted to define the strength of the roadbed at various discrete locations on the test sections. The FWD consists of a flat plate that is pushed into the road with a known force. The force with which the road 'pushes back' is then recorded and gives a measure of road strength. Road strength varies significantly with seasons therefore the FWD testing was conducted seasonally. [4]

3 ANALYSIS

The test data were contained in three separate data files:

- Truck data – which contained the engine data, and included date and time, vehicle speed, engine RPM, fuel flow, throttle position;
- Wind data – data from the front boom mounted anemometer
- Test log file – Notes which include test data on vehicle weight, pavement temperatures, ambient temperatures, and general notes and observations.

In addition, the test site data were contained in three files:

- GPS topography data
- A seasonally specific IRI data set.
- A seasonally specific FWD data set.

All these files were merged into one unified data set. The truck and wind data were time based data sets (a reading at defined time intervals), which located the physical site data in space (distance along road). The merging process involved converting the vehicle's time-based data to space-based data by estimating distance travelled between sampling time intervals (speed/time) and locating the start distance for the test. The GPS and IRI data were merged in space and time respectively based on the truck data file's distance and time for the start of the test. Test load and temperatures were added to each test record along with the pavement structure data. The final "metafile" contained all the test data in a unified frame of reference. Finally all the test data, by season, was formed into one data file (without formulae) and analysed using the software package Minitab.

3.1 Statistical Analysis

Multiple regression was used to investigate the effects of pavement structure on fuel consumption rate. Data filtering was employed on the total data set to remove spurious data and also to constrain the data within designated speed zones (removing speed transition data) and pavement roughness ranges. Post-test analysis revealed that the roads were significantly smoother than previous studies, therefore the initial maximum value of IRI equalling 2.0 was reduced to a maximum value of 1.6 for the Phase III data. Fuel consumption data collected on pavements with an IRI greater than 1.6 were thus not considered as part of the Phase III analysis. The differences in pavement structure relative to concrete were represented in the model by two indicator values: Pvash and Pvcomp:

- the first took on a value of one (1) for asphalt and zero (0) otherwise,
- the other took a value of one (1) for composite and zero (0) otherwise.

Thus, concrete pavement was defined as the base category or structure. The analysis developed a model which estimated fuel consumption rate (L/100km) as a function of pavement structure, vehicle load, air or pavement temperature, vehicle speed, wind speed, IRI, grade, and various interactions among these variables. It was determined that the following single equation form could be applied to all the seasonal subsets and to the combined data set.

FuelCon = Constant + Pvash * (1=asphalt) + Pvcomp * (1=composite) + IRI coeff * IRI + Grade coefficient * Grade + Load coeff * Load + Pavement temperature coefficient * Pavetemp + Speed coefficient * Speed + AirSpdSq coefficient * AirSpdSq

Where:
FuelCon = fuel consumption rate in L/100km
IRI = International Road Roughness Index
Grade = Road grade in percent
Load = Total vehicle mass in kilograms
Pavetemp = Pavement or ambient temperature in degrees Celsius
Speed = Vehicle road speed in km/h
AirSpdSq = Absolute air speed (road speed plus relative wind speed) squared.

This equational form provided the best explanatory power of a number evaluated and contained all the variables measured in the study.

In order to ensure that the data was collected in a repeatable and defensible manner, the driver of the truck was periodically asked to drive the same stretch of road, at the same speed, on the same night. Figure 1 illustrates the results of such an exercise and shows good repeatability, overall.

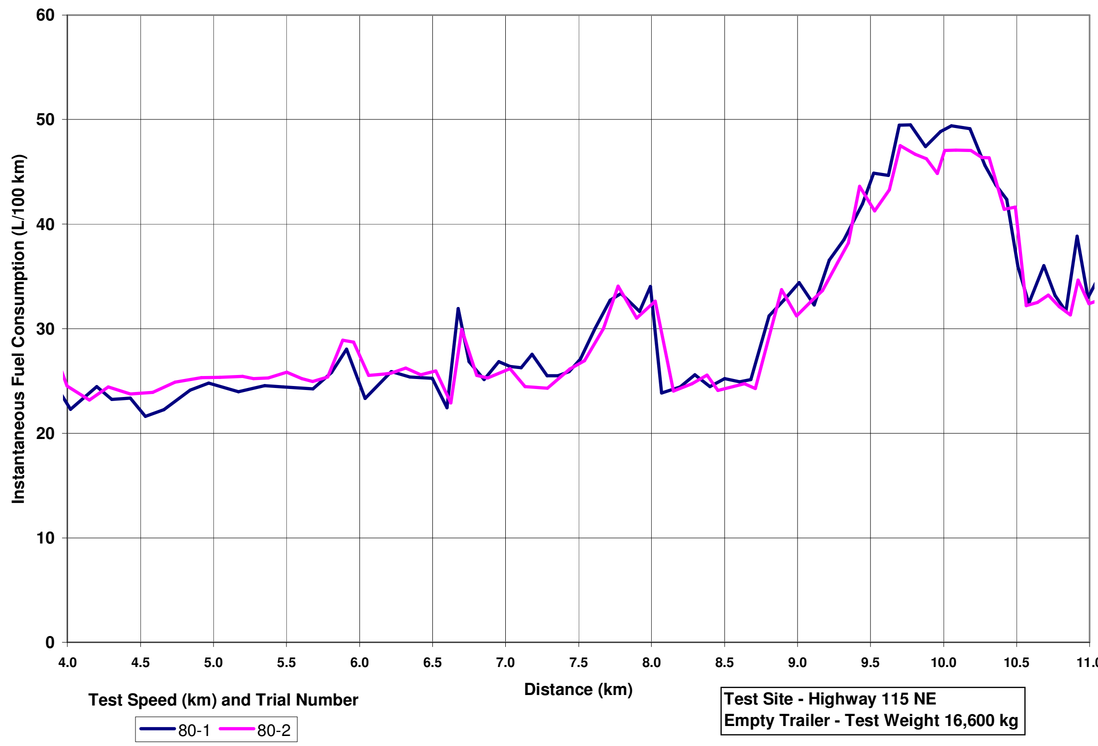

Figure 1 - Repeatability Curve

4 RESULTS

The results of this statistical analysis were as follows:

At 100 km/h, on smooth roads, fuel consumption reductions were realised on all concrete roads when compared to asphalt. The savings ranged from 0.4 L/100 km to 0.7 L/100 km (0.8% to 1.8%) when compared to asphalt roads. These savings were realised for both empty and fully loaded vehicle conditions for four of the five seasons. All these differences were found to be statistically significant at the 95% level. The savings during the fifth season, Summer Night, were 0.25 L/100 km (0.4%), however, these data were found to be not statistically significant. See Figure 2.

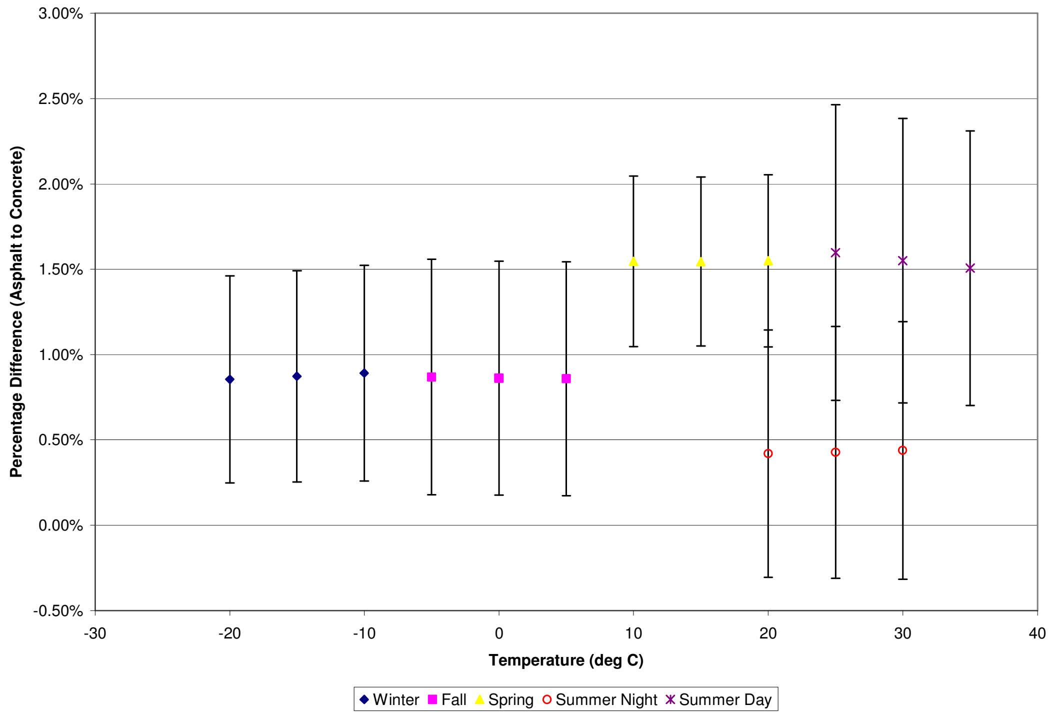

Figure 2 - Fuel consumption differences between asphalt and concrete, 100 km/h, full load

When comparing concrete roads to composite roads at 100 km/h, the results showed that fuel consumption savings ranged from 0.2 L/100 km to 1.5 L/100 km (0.8% to 3.1%) in favour of concrete. However, under Summer day conditions, less fuel was consumed on the composite roads, as compared to concrete. The value of these savings was roughly 0.5 L/100 km (1.5%). All composite to concrete comparisons were found to be statistically significant except the Spring data, which was not statistically significant. See Figure 3.

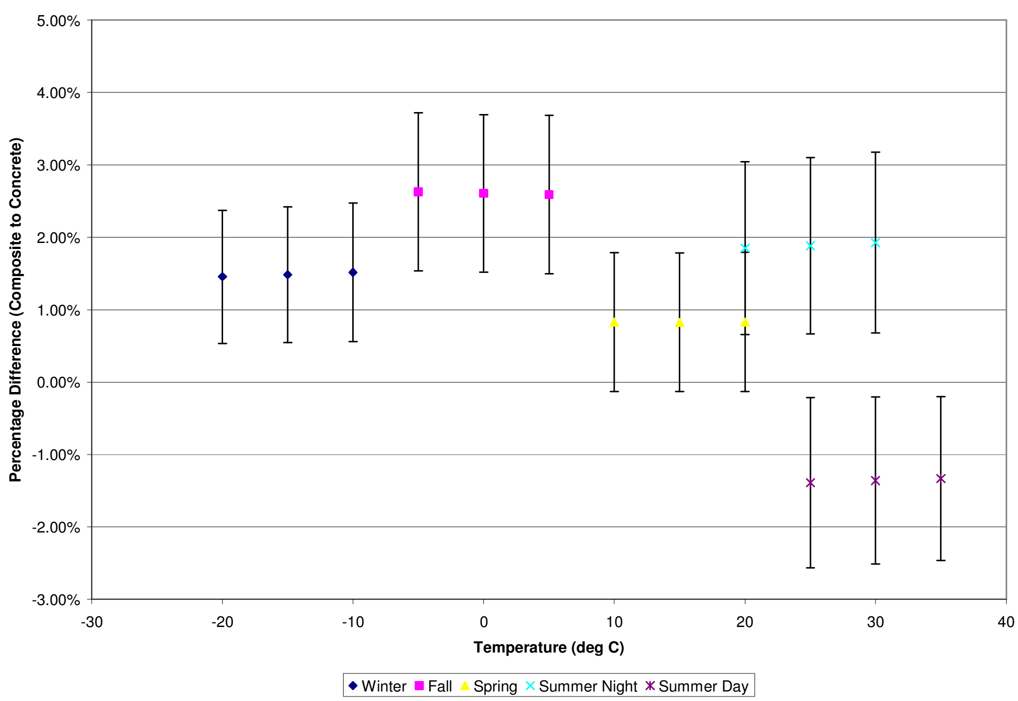

Figure 3 - Fuel consumption differences between composite and concrete, 100 km/h, full load

The fuel savings for the empty trailer at 60 km/h when comparing concrete to asphalt roads ranged from 0.4 L/100km to 0.5 L/100km (1.7% to 3.9%) in favour of concrete and were all statistically significant in four of the five seasons. The fuel savings for the Summer Night data were 0.1 L/100 km (0.5%) but they were not statistically significant.

The fuel savings for the full trailer at 60 km/h when comparing concrete to asphalt roads ranged from 0.2L/100km to 0.4 L/100km (1.3% to 3.0%) in favour of concrete and were all statistically significant. The fuel savings for the Summer Night data were 0.1 L/100 km (0.5%) but they were not statistically significant. See Figure 4.

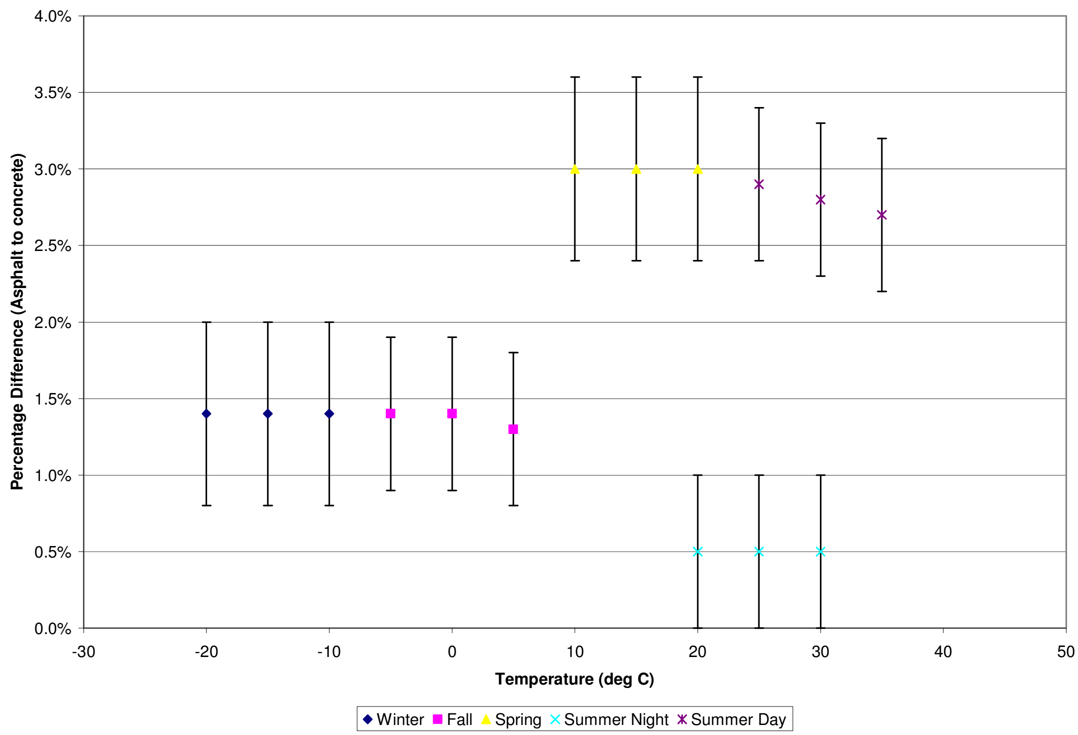

Figure 4 - Fuel consumption differences between asphalt and concrete, 60 km/h, full load

The fuel savings for the empty trailer at 60 km/h in four of the five seasons when comparing concrete to composite roads ranged from 1.1 L/100km to 1.9 L/100km (2.0% to 6.0%), in favour of concrete. However, the summer day data indicated a savings in favour of composite, when compared to concrete, of 0.2 L/100 km (3.0%). All of these savings were statistically significant.

The fuel savings for the full trailer at 60 km/h in four of the five seasons when comparing concrete to composite roads ranged from 0.6 L/100km to 1.4 L/100km (1.9% to 4.1%) in favour of concrete. However, the summer day data indicated a savings in favour of composite, when compared to concrete, of 0.2 L/100 km (2.4%). All of these savings were statistically significant except the Spring data. See Figure 5.

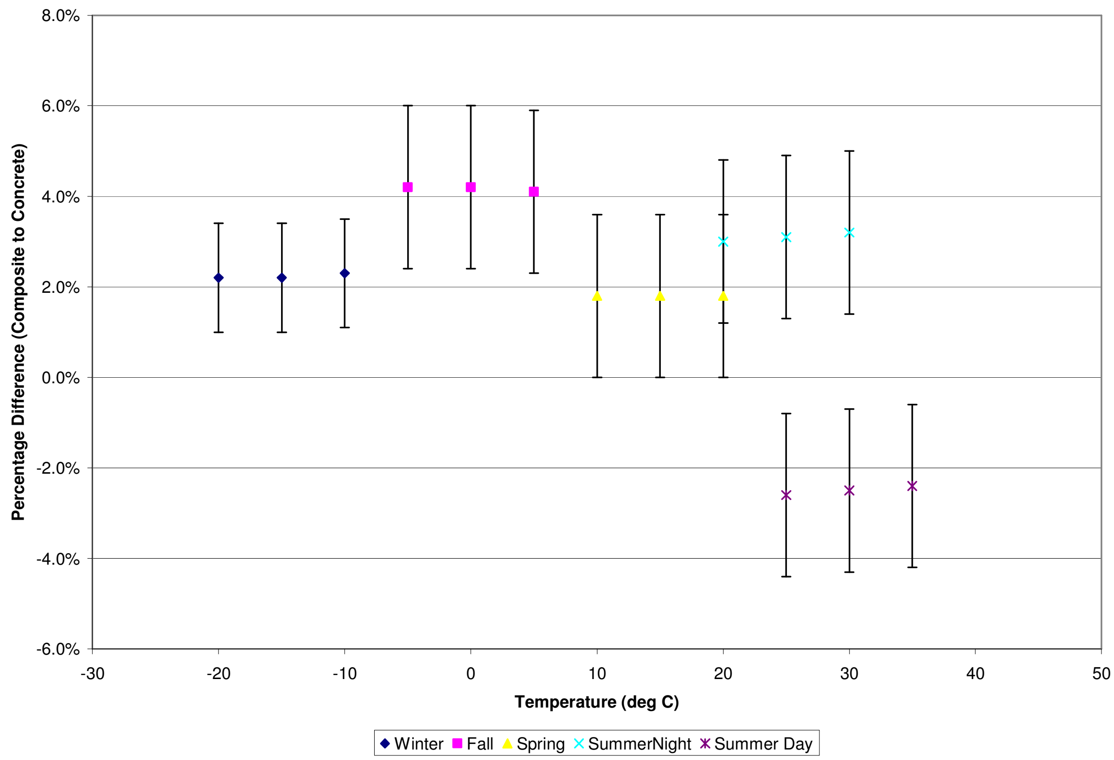

Figure 5 - Fuel consumption differences between composite and concrete, 60 km/h, full load

Separate from the cruise tests performed at 100 km/h and 60 km/h, coastdown tests were conducted on the fully loaded tractor and van semi-trailer combination to isolate the differences in rolling resistance between the three pavement surfaces. The fully loaded tractor and trailer were driven at 30 km/h and then allowed to coast down to 10km/h. These slower speeds were chosen to isolate the contribution of deceleration from the road/tire interaction while minimizing aerodynamic effects. Additionally it was not deemed safe to bring the vehicle to 0 km/h on an open stretch of highway. The results of the coastdown testing did not indicate any significant differences between any of the three surfaces with respect to rolling resistance, from 30 km/h to 10 km/h.

CSTT performed a comparison between this Phase and the previous Phase II rework project. Since each project generated a data set and a model it stood to reason that each of the data could be plugged into each of the models. The results of this cross-comparison are listed below:

Different mathematical models were developed for the Phase II and Phase III studies. The data from both studies (Phase II and Phase III) were analyzed and compared using both models for the data collected at 25 deg C. For the Phase II data (tanker semi-trailer), these analyses showed statistically significant fuel savings when operating on concrete pavement compared to asphalt pavement of 1.9 L/100 km, ranging from 4.3% to 9.2%, depending on model used, IRI range, vehicle speed and weight. It is important to note that these higher percentage differences between the two data sets were likely affected by the different types of road surfaces and not the models

When similarly comparing concrete pavement and composite pavement, the savings ranged from 0.8 L/100 km to 1.2 L/100 km (1.9% to 5.8%) in favour of concrete.

The comparison using the two models for the Phase III (van semi-trailer) data at 25 deg C showed statistically significant fuel savings when operating on concrete pavement compared to asphalt pavement ranging from 0.5 L /100 km to 0.8 L/100 km (1.1% to 5.2%), depending on model used, IRI range, vehicle speed and weight.

The comparison using the two models for Phase III data (van semi-trailer) showed that the fuel consumption differences between composite and concrete pavements on rougher roads were not statistically different. However, the fuel consumption savings for concrete pavements, when compared to composite, on smoother roads ranged between 0.3 L/100 km and 0.7 L/100 km (0.6% and 4.8%) and were all statistically significant.

The predicted fuel savings on concrete, when compared to asphalt and composite, are very similar when Phase III data (van semi-trailer) is inserted into each of the models. Similarly, the predicted fuel savings on concrete, when compared to asphalt and composite, are very similar when Phase II data (tanker semi-trailer) is inserted into each of the models. However, the predicted fuel savings when comparing Phase II data to Phase III data are not similar. CSTT therefore concludes that the differences between Phase II and Phase III results stem primarily from the collected data themselves (i.e. the prevailing road conditions) and not the mathematical models.

5 REFERENCES

[1] Effect of Pavement Surface Type on Fuel Consumption, Phase II, CSTT-HVW-CTR-041, Taylor, Marsh, Oxelgren, August 2000.

[2] Additional Analysis of the Effect of Pavement Structure on Truck Fuel Consumption, Taylor, GW, July 2002.

[3] http://www.umtri.umich.edu/erd/roughness/iri.html.

[4] http://www.dynatest.com/hardware/fwd_hwd.htm.