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# Test Report

# Effects of Pavement Structure on Vehicle Fuel Consumption – Phase III

G.W. Taylor, P. Eng.
J.D. Patten, P. Eng.

**Centre for Surface Transportation Technology (CSTT)**
**National Research Council of Canada (NRC)**
2320 Lester Road
Ottawa, Ontario K1V 1S2
Canada

Phone (613) 998-9639
Fax (613) 957-0831

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Rapport technique

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J. Coleman
General manager/
Gestionnaire principal

# ABSTRACT

A highway tractor with a van semi-trailer and a passenger car were driven over concrete, asphalt and composite 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 cool, summer hot 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.

# EXECUTIVE SUMMARY

The Pavement Fuel Efficiency Study, Phase III was contracted by the Cement Association of Canada (CAC) and Natural Resources Canada (NRCan) under the Government of Canada Action Plan 2000 on Climate Change (Minerals and Metals Programme), in the fall of 2002, to the National Research Council's (NRC) Centre for Surface Transportation Technology (CSTT). CSTT provided an independent third-party evaluation to quantify the potential fuel consumption differences when vehicles are driven over three distinct types of pavements: asphalt, concrete and composite (asphalt top-coat over concrete).

CSTT developed comprehensive performance tests that were conducted between fall 2002 and fall 2003 to quantify these potential fuel consumption differences for a highway tractor pulling a loaded van semi trailer. Additionally, limited data were also collected for a passenger car. The passenger car was tested in one loading condition, winter and summer weather conditions over all three pavement types. The highway tractor and tridem van semi-trailer were tested in three loading conditions, at five distinct seasonal conditions (winter, summer day [hot], summer night [cool], fall and spring) and over all three pavement types.

The results of the study pertain to the test routes that were selected for this programme and not necessarily all grades of concrete, asphalt and composite pavements. Additionally, there was no attempt to quantify the effects of periodic surface irregularities such as potholes, low friction/high friction transient areas, tining and changes in elastomeric properties. The study was focussed on fuel burn characteristics and did not consider such pavement properties as light reflection, sound reflection, resistance to hydroplaning, maintainability or ease/cost of construction.

In addition to the dynamic fuel consumption data, a series of static surveys were conducted to characterize the road surfaces. An IRI survey was used to gather information on International Roughness Index, an index that measures irregularities on the surface of the road (lower values of IRI equate to smoother roads). A precision GPS survey was used to gather information on road curvature and grade. Finally, a Falling Weight Deflectometer survey was conducted to quantify the strength of the road bed at selected locations. The data from these surveys were merged with the fuel consumption data to form 'Meta' files. These 'Meta' files were then used to generate models for all the various conditions, allowing statistical multiple regression formulae to be generated.

CSTT's conclusions, stemming from the tractor and van semi-trailer fuel consumption testing and subsequent statistical models, are summarized below. Unless noted otherwise, all values of absolute fuel consumption differences are mean values and all percentage differences are mean percentage differences:

- 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.

- 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.

- 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 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 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.

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 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's primary conclusions stemming from the passenger car testing and subsequent statistical models are summarized below:

- Due to the limited number of data points and seasonal conditions, the results from the passenger car testing were less conclusive than the tractor and trailer testing.

- Of the four seasonal car models presented below, three were statistically significant and one was not (asphalt versus concrete in summer).

- In winter testing, the passenger car consumed 0.3 L/100 km more (2.9%) on asphalt than on concrete. These savings were all statistically significant.

- In winter testing, the car consumed 0.2 L/100 km less fuel (2.3%) on composite pavement when compared to concrete. These savings were all statistically significant.

- In summer testing, the passenger car consumed 0.1 L/100 km (1.5%) more fuel on composite roads when compared to concrete. These savings were all statistically significant.

- In summer testing, the passenger car consumed 0.05 L/100 km (0.3%) less fuel on asphalt roads when compared to concrete. However, these savings were not statistically significant.

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 on smooth roads and were statistically significant.

- 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.

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Report prepared by

**Gordon Taylor, P. Eng.**
Consulting Engineer

Reviewed and approved by

**Jeff Patten, P. Eng.**
Manager, Test and Evaluation Engineering
Road Vehicles and Military Systems
NRC/CSTT

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- Erik Oxelgren set up the data acquisition system and acquired fuel burn data and monitored the testing for every tractor trailer test loop. The vast majority of the tests were conducted between 6 PM and 4 AM. Mr. Oxelgren’s dedication to the project is greatly appreciated;

- Rebecca Mann performed data acquisition on several of the passenger car runs; and

- Cristian Tabra, E.I.T assisted with passenger car testing.

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# 1 INTRODUCTION

## 1.1 References

A. Statement of Work between Cement Association of Canada and NRC/CSTT, dated 8/2002.
B. Interdepartmental agreement between NRC/CSTT and Action Plan 2000 on Climate Change, Minerals and Metals (NRCan), signed 3/21/2003, amended 6/17/2003 and 4/4/2004.

## 1.2 Task Objective

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.

## 1.3 Previous Work

Prior to the commencement of this Phase III testing, the National Research Council and the Cement Association of Canada had engaged in two previous pavement fuel efficiency studies. Each of the previous phases identified areas of concern and possible improvement for future studies. Phase I was a single season test designed as an initial body of work to determine if fuel efficiency differences between concrete and asphalt pavements could be detected, using engine management software. Phase II was a multi-season test involving a variety of different truck and trailer combinations and a relatively wide spectrum of road roughness and was a more in depth study than Phase I. After Phase II was delivered it was determined that a more thorough statistical model would allow for better interpretation of the results. Therefore, a Phase II “rework” project was initiated to build a more robust statistical model using the Phase II data (tanker semi-trailer only).

The lessons learned in Phases I and II were reviewed, allowing a more focussed and representative study to be conducted, called Phase III. This technical report deals primarily with the execution, analysis and results of Phase III testing. However, where appropriate, previous phases have been presented, discussed and compared to Phase III work. The following table outlines the time-lines of each of the phases:

| **Phase** | **Data Collection** | **Report Acceptance** |
|---|---|---|
| **I** | Summer 1998 | November 1998 |
| **II** | April 1999 to January 2000 | August 2000 |
| **II Rework** | April 1999 to January 2000 | July 2002 |
| **III** | Sept 2002 to Sept 2003 | December 2005 |

### 1.4 Overview for Phase III

The third phase of testing was complementary to the previous two phases [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. Section 7 outlines the principal differences regarding methodology and conclusions between Phases II and III.

Although the main objective of this Phase III study was to quantify the fuel efficiency of a heavy haul tractor-trailer combination, a passenger car component was added to the test programme, to broaden the spectrum of analysis. The results from truck and passenger car testing are presented separately, in subsequent sections of this report.

### 1.5 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 EQUIPMENT, PROCEDURES & TEST PARAMETERS

## 2.1 Equipment

The following equipment was used:

i. “International” tandem drive axle, tractor unit.
ii. Wabash, 53 foot, tridem axle, van semi trailer.
iii. 2002 Pontiac Grand Prix, VIN 1G2WK52J72F224037
iv. Data acquisition computers and peripherals
v. Hand held temperature probe
vi. AutoTAP hardware and software
vii. Payload in the form of lead boxes and concrete filled drums c/w tie downs
viii. Wind speed anemometer
ix. Single roller dynamometer
x. Laptop computers
xi. Power inverter
xii. Barometer
xiii. Autologger
xiv. Cummins “Insite” Version 5.4 software and adapter
xv. Flashing lights
xvi. Rotating beacon

## 2.2 Vehicle tests performed by NRC/CSTT

The fuel efficiency data were collected using two separate vehicles:

- Heavy haul tractor with semi trailer; and
- Passenger car.

The test apparatus and methods for each configuration are presented separately below.

## 2.3 Heavy Haul Tractor with Semi Trailer

### 2.3.1 Apparatus

Previous NRC pavement fuel efficiency studies used truck and trailer combinations that were less common to Canadian roads. Although data collected in previous studies were relevant to the road surfaces found in Canada, they did not properly represent the majority of tractor/trailer combinations found on Canadian roads. In order to alleviate this problem, the most commonly used combination was selected for this phase of testing: a single axle- steer with tandem-drive-tractor pulling a 53-foot dry goods van semi trailer.

Although the tandem-axle van semi trailer remains the most popular axle arrangement in Ontario and Quebec, a 12 foot spread tridem (three axle) trailer arrangement was selected for two reasons: tridem grouping provides 12 tires in contact with the road, in comparison with eight tires for a tandem, thus providing more statistical sensitivity to rolling resistance for a study of this nature; and the tridem grouping is becoming increasingly more popular as operators attempt to ship heavier loads using the same length of trailer.

A manufactured, and variable, load was created from lead boxes weighing from 500 to 5000 lbs each, as well as barrels filled with concrete, each weighing 1000 lbs. This allowed the test team to load the trailer to any gross weight stipulated by the test parameters. The concrete barrels were tightly secured to the van trailer using cargo straps and were prevented from moving in any direction. A railway system was screwed to the floor of the trailer to prevent the lead boxes from moving laterally or longitudinally, however, the boxes were able to move vertically, with the motion of the trailer, by roughly one inch (2.5 cm).

With the exception of the manufactured load of lead and concrete, both the tractor and trailer were tested in a completely ‘stock’ condition and represented a typical Ontario/Quebec configuration. None of the tires were replaced during the tests and no major tractor power-train components were replaced other than fluids and filters. The tires used for testing (manufactured by General Tire) were neither ‘low rolling resistance’ or ‘high rolling resistance’ and represented a typical set of tires used in Canada. The test truck, trailer and load can be seen at Figures 2-1 and 2-2.

Figure 2-1 Side View of Tractor Trailer

Figure 2-2 Trailer Payload giving 49,400 kg GVW

Due to logistical reasons, beyond the control of CSTT/NRC, the tractor was not equipped with a roof mounted air deflector. Although reducing the effects of aerodynamic drag would have been ideal, the net effect on the mathematical models can be considered minimal since the identical tractor and trailer were used throughout all phases of testing. When considering how a tractor's power (leaving the drive-shaft) is consumed while cruising on the highway, three factors should be considered: aerodynamic drag, rolling resistance and electrical/HVAC accessories. Horizontal trailer aerodynamic drag can typically be modelled as a quadratic curve ($y = ax^2 + b$) whereas rolling resistance is a linear form such as $y = mx + b$. The contribution of electrical and climate control accessories are normally modelled as a constant. The contributions of vertical aerodynamic effects have been ignored.

Since this study focussed on fuel burn as it relates to pavement type it would have been ideal to isolate the contribution from rolling resistance and remove all other sources (i.e. remove the possibility that high speed aero drag may reduce the sensitivity of the rolling resistance data). However, when measuring total actual fuel burn over a specified distance it is impossible to distinguish the fuel burn's various sources. An analysis of that nature could only be developed using theoretical estimates or computer simulations.

The following example (using industry accepted figures [3], [4], [5]) demonstrates how the model could have been affected by the lack of air deflector at higher speeds:

Without an air deflector, at 100 km/h, the power delivered by a typical tractor is consumed as follows (excluding internal losses in the engine itself):

| | | |
|---|---|---|
| 82 kW | Aerodynamic Drag | 51% |
| 60 kW | Rolling resistance | 38% |
| 18 kW | Electrical Accessories/AC | 11% |
| **160 kW** | **Total** | **100%** |

Under similar conditions, the power drain on a tractor fitted with an air deflector would be:

| | | |
|---|---|---|
| 70 kW | Aerodynamic Drag | 47% |
| 60 kW | Rolling resistance | 41% |
| 18 kW | Electrical Accessories/AC | 12% |
| **148 kW** | **Total** | **100%** |

Therefore, the sensitivity of analysing the high speed fuel efficiency data, based on rolling resistance figures without an air deflector, would likely be less than 4% (i.e. 4% applied to the *difference* in fuel economies between the pavement types, which itself is already a small number). The low speed data would not be affected since aerodynamic drag is insignificant at city speeds.

### 2.3.2 Test Conditions

The tractor semi-trailer was tested in five separate temperature ranges as follows:

| Season | Ambient Temperature Range |
|---|---|
| Winter | < -10 $^{o}$C |
| Spring | > - 5 $^{o}$C and < +10 $^{o}$C |
| Summer Hot | > +29 $^{o}$C |
| Summer Cool | > +10 $^{o}$C and < +25 $^{o}$C |
| Fall | > - 5 $^{o}$C and < +10 $^{o}$C |

Note: Although the ambient temperature range for fall and spring were identical, roads can behave differently in different seasons due to variations in roadbed strength.

The tractor semi-trailer was tested using three separate loading conditions as follows:

| Load Condition | GVW |
|---|---|
| Empty | 16,000 kg |
| Practical Full Load | 43,660 kg |
| Maximum Legal Load in Ontario/Quebec | 49,400 kg |

Note: Weights recorded on MTQ and MTO scales.

The load conditions were selected for the following reasons:

**Empty**: This represented a situation when a trailer has delivered its load and is returning to its point of origin.

**Nominal Full Load**: This represented a typical situation where a trailer is loaded to its maximum *nominal* weight with allowances for variations in payload location, snow and rain loading, extra passengers and fuel. This load situation, although not at the legal limit, is the practical limit used by most operators. It is very difficult to configure a vehicle at maximum legal gross weight while simultaneously satisfying individual load restrictions on each axle group.

**Maximum Legal Load**: This represented the maximum permissible loading as stipulated by the Ministries of Transportation in Quebec and Ontario. Although this load is legal, it is not practical for normal revenue service as it requires delicate balancing of gross weight and individual axle loads.

Table 2-1 summarizes the test sites and the acceptable test conditions and parameters used to acquired the data.

**Table 2-1 Summary of Test Sites and Initial Test Conditions**

| Variable | Number of Conditions | Locations or Test Conditions |
|---|---|---|
| Pavement Structural Types | 3 | Concrete<br>- Highway 440E/W, Laval, QC<br>- Highway 13N, Laval, QC<br>- Highway 40E/W, Vaudreuil, QC<br>- Highway 417 E , East of Casselman, ON<br>- Highway 115W, Peterborough,ON<br><br>Asphalt<br>- Highway 40E, Rigaud, QC<br>- Highway 25 Laval, QC<br>- Highway 40W/E near Vaudreuil, QC<br>- Highway 417E, Carp, ON<br>- Highway 115E, Peterborough, ON<br>- Highway 417E, Casselman, ON<br>- Highway 115W, Peterborough,ON<br><br>Composite(Asphalt/Concrete)<br>- Highway 440 W Laval, QC<br>- Highway 401W, Morrisburg, ON |
| Pavement Roughness | Variable | IRI < 2 |
| Vehicle Types | 1 | 3 axle tractor with tridem (3 axle) van semi-trailer. |
| Load | 3 | Empty – 16,000 kg<br>Typical Full – 43,660 kg<br>Maximum Legal – 49,400 kg |
| Speed | 3 | 100, 80, 60 km/h |
| Seasons | 5 | Spring, Summer Night, Summer Day, Fall and Winter |
| Temperatures Ranges | 4 | Less than –10 $^{o}$C ,<br>-5 to 10 $^{o}$C<br>10 to 25 $^{o}$C<br>Greater than 25 $^{o}$C |
| Ambient Wind | Variable | Less than 10 km/h average |
| Grade | Variable | Less than 0.5% |
| Road Conditions | | Bare and dry |

### 2.3.3 Test Procedure

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 kilometres from CSTT which allowed the powertrain, wheel bearings and tires to become sufficiently warm.
v. Several kilometres before the start of a test site, the data acquisition system was readied and zeroed and 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.
vi. As the tractor passed the established kilometre 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 80 km/h and 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.

## 2.4 Passenger Vehicle

### 2.4.1 Apparatus

To complement the tractor and trailer testing, a series of passenger car tests were conducted. The test car was a 2002 Pontiac Grand Prix four-door sedan equipped with a 3.1 L V6 engine, four speed automatic transmission and Good-Year Eagle L/S tires. The vehicle was received off-lease with 42,000 km, ensuring that the engine was "broken in". The tires were inspected and found to be in excellent, and similar, condition. See Figure 2-3.

**Figure 2-3 Front Three Quarter View of Pontiac Grand Prix**

### 2.4.2 Test Conditions

The passenger car was tested in two (2) separate temperature ranges as follows:

| **Season** | **Ambient Temperature Range** |
|---|---|
| Winter | < -10 $^{o}$C |
| Summer Cool | >+15 $^{o}$C and < +25 $^{o}$C |

These temperatures were selected to give a broad range of data, while respecting the limited time allotted for car testing.

The passenger car was tested using one load condition as follows:

| **Load Condition** | **Weight** |
|---|---|
| Curb weight, 2 occupants and baggage | 1756 kg |

### 2.4.3 Test Methodology

The test methodology used for the passenger car was similar to that of the tractor semi-trailer except that the software used to acquire these data was specifically written for General Motors vehicles, and hence acquired a different set of engine parameters.

## 2.5 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. For a full description of IRI refer to: http://www.umtri.umich.edu/erd/roughness/iri.html.

**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. For a full description of FWD refer to http://www.dynatest.com/hardware/fwd_hwd.htm.

# 3 TEST SITES

## 3.1 Test Site Descriptions

The test sites were developed jointly by NRC/CSTT and the client steering committee. The objective was to find multiple road sites that were constructed in concrete, asphalt and composite (concrete base with asphalt top layer), were nominally flat and straight, had IRI values less than 2.0 and were within a daily operational radius of NRC/CSTT offices in Ottawa. The steering committee suggested a series of sites and site evaluation trips were made to all the proposed sites during the last two weeks of August 2002. Each site was assessed for its topography, operational feasibility, total test loop distances and estimated test times. After these assessments, and some further site modifications, the following sites were selected for inclusion in the program:

Site 1: 417E/W (West of Kanata) Asphalt
This section ran between Panmure Rd. (kilometre post (kp) 163) and March Rd. exit (kp 144). It had significant grades at the westerly end of the section but this deficiency was offset by a series of flat areas in the easterly end. Both directions were included in the test section.

Site 2: 417E Concrete
This section started at kp 44.5 and ended at kp 9 and represented a newly constructed section of highway. Because of the extremely long distance between loop-around points in this section, it was recommended that only one direction be used and that the speed test be done sequentially (100, 80 and 60) through the section.

Site 3: 40E/W Rigaud Asphalt
This section started at kp 13 and ended at kp 8 on Highway 40 in Quebec just before the Hudson off-ramp. The easterly direction was originally specified but the westerly direction was added as it was part of the loop back.

Site 4: 40E/W Hudson-Vaudreuil Concrete/Asphalt
This was a site that had been used in the Phase II testing (tanker trailers). The section starts at kp 26, ends at kp 37, and has both asphalt and concrete pavements. The center section contains an overpass and does not meet grade criteria (data taken on the overpass was omitted from the analysis).

Site 5: 401E/W Morrisburg Composite
This section was on Highway 401 starting at kp 758 and ending at kp 738 near Morrisburg, Ontario. This is a long section and thus sequential speed tests were performed over 7 km length sections. Originally only the westerly direction was to be used but the easterly section was resurfaced just prior to the testing program’s start and was thus included in the study.

Site 6: 13N/S Laval Concrete
This section started at kp 10 and ended at kp 19.5 on Highway 13 (Quebec) with both directions used. Loop backs were made at interchanges 20 and 8.

Site 7: 440/25 E/W Laval Concrete, Asphalt
This site was included in the previous study and contains both a concrete portion (Highway 440) and an asphalt portion (Highway 25). The start and end points were at kp 18 and kp 15.5 on Highway 25, and kp 18 and kp 31 on Highway 440. Testing was done in both directions.

### Site 8: 40W Kirkland Asphalt

This section between kp 49 and kp 40 (Exit 40) was not included in the originally suggested test sections but is quite flat and is on a route coming back from Site 6/7. The site was included with testing at a constant speed (100 km/h).

### Site 9: Hwy 115 NE/SW Concrete and Asphalt

This section of Highway 115 is constructed with alternating sections of concrete and asphalt pavements. Some portions of the route have excessive grade, however, there are level sections available for both pavement types. Loop arounds were done at interchanges for Highway 7A and County Rd 32. Note that there are no kilometre posts on this highway and thus roadside physical start and end queues were used. The north-easterly direction start was at the “no U turn” sign and ended at the Highway 7A exit – “Fowler's Corners” exit sign. The south-westerly start was opposite the Highway 7A exit – “Fowler's Corners” exit sign on the NE pavement.

### Sites 10 and 11: 417E Asphalt

Sites 10 and 11 were added as they were sections of highway that were driven over to get to Site 2 on Highway 417. Site 11 was a portion of the test site used in the previous study near the Casselman test site (kp 64 to kp 52). Site 10 is a very long section of flat asphalt from kp 103 through to kp 64. Both sections were tested in a single direction (east) at a single highway speed of 100 km/h. Note that no IRI data were collected for these sections but they were judged to be in good repair with estimated IRI values between 1 and 2.

The test site locations and lengths are summarized in Table 3-1 and indicate that a total of 268.3 linear km of road was used in the study. Given the number of test loads, speeds and temperature conditions included in the study, a total of 8,954 km of test surfaces were driven over to collect 736 data files.

Tables 3-1 through 3-4 illustrate the IRI, grade and curvature data for all of the test sites. However, it should be noted that the data presented represents every metre of the test sites but some of this data were rejected from the analysis as it was outside of the test parameters.

## Table 3-1 Test Site Lengths and Characteristics, Sorted by Test Site

| Site No. | Province | Location | Asphalt (km) | Concrete (km) | Composite (km) | Average IRI* | Average %Grade | Average %Curve | Maximum % Grade | Minimum % Grade |
|---|---|---|---|---|---|---|---|---|---|---|
| 1E | Ontario | Highway 417 | 6.4 | | | 0.9 | -0.44 | -0.03 | +3.2 | -1.9 |
| 1W | Ontario | Highway 417 | 7.6 | | | 0.8 | 0.45 | -0.01 | +1.8 | -2.1 |
| 2E | Ontario | Highway 417 | | 38.9 | | 1.1 | 0.01 | -0.04 | +3.2 | -1.9 |
| 3E | Quebec | Highway 40 | 2.9 | | | 1.1 | 0.16 | 0.18 | +1.0 | -0.9 |
| 3W | Quebec | Highway 40 | 3.5 | | | 1.2 | -0.11 | -0.16 | +0.9 | -1.2 |
| 4E | Quebec | Highway 40 | 7.5 | | | 1.8 | -0.35 | -0.08 | +1.0 | -0.9 |
| 4E | Quebec | Highway 40 | | 3.4 | | 1.3 | -0.35 | -0.08 | +1.0 | -0.9 |
| 4W | Quebec | Highway 40 | 7.4 | | | 1.8 | 0.38 | 0.10 | +0.9 | -1.2 |
| 4W | Quebec | Highway 40 | | 3.4 | | 1.1 | 0.38 | 0.10 | +0.9 | -1.2 |
| 5E | Ontario | Highway 401 | | | 19.8 | 0.6 | -0.01 | 0.01 | +0.8 | -1.1 |
| 5W | Ontario | Highway 401 | | | 19.8 | 0.9 | -0.01 | -0.01 | +0.9 | -1.1 |
| 6N | Quebec | Highway 13 | | 9.3 | | 1.3 | 0.02 | 0.01 | +2.3 | -2.1 |
| 6S | Quebec | Highway 13 | | 9.4 | | 1.2 | -0.01 | 0.00 | +1.8 | -0.9 |
| 7N | Quebec | Highway 25 | 2.7 | | | 1.4 | -0.01 | -0.07 | +2.0 | -2.9 |
| 7E | Quebec | Highway 440 | | 13.0 | | 1.4 | -0.01 | -0.07 | +2.0 | -2.9 |
| 7S | Quebec | Highway 25 | 2.5 | | | 1.3 | 0.03 | -0.04 | +3.1 | +2.1 |
| 7W | Quebec | Highway 440 | | 13.3 | | 1.4 | 0.03 | -0.04 | +3.1 | +2.1 |
| 8W | Quebec | Highway 40 | 11.1 | | | 1.3 | -0.06 | 0.08 | +0.9 | -1.2 |
| 9NE | Ontario | Highway 115 | 7.3 | | | 1.0 | -0.92 | 0.01 | +3.3 | -2.3 |
| 9NE | Ontario | Highway 115 | | 7.5 | | 1.7 | -0.92 | 0.01 | +3.3 | -2.3 |
| 9SW | Ontario | Highway 115 | 3.1 | | | 1.2 | 0.92 | -0.04 | +2.6 | -3.4 |
| 9SW | Ontario | Highway 115 | | 14.4 | | 1.5 | 0.92 | -0.04 | +2.6 | -3.4 |
| 10E | Ontario | Highway 417 | 39.9 | | | n/a | -0.05 | -0.02 | n/a | n/a |
| 11E | Ontario | Highway 417 | 14.0 | | | n/a | 0.02 | -0.05 | n/a | n/a |
| Total | | **Total = 268.3km** | **115.9km** | **112.8 km** | **39.6 km** | | | | | |

- International Roughness Index - summer values
- Grades greater than 0.5% were rejected in the mathematical models
- 10E and 11E were sections from previous studies and no IRI data were collected

## Table 3-2 Test Site Lengths and Characteristics, Sorted by Pavement Type

| Site No. | Province | Location | Asphalt (km) | Concrete (km) | Composite (km) | Average IRI* | Average %Grade | Average %Curve | Maximum % Grade | Minimum % Grade |
|---|---|---|---|---|---|---|---|---|---|---|
| 7S | Quebec | Highway 25 | 2.5 | | | 1.3 | 0.03 | -0.04 | 3.1 | 2.1 |
| 7N | Quebec | Highway 25 | 2.7 | | | 1.4 | -0.01 | -0.07 | 2.0 | -2.9 |
| 3E | Quebec | Highway 40 | 2.9 | | | 1.1 | 0.16 | 0.18 | 1.0 | -0.9 |
| 9SW | Ontario | Highway 115 | 3.1 | | | 1.2 | 0.92 | -0.04 | 2.6 | -3.4 |
| 3W | Quebec | Highway 40 | 3.5 | | | 1.2 | -0.11 | -0.16 | 0.9 | -1.2 |
| 9NE | Ontario | Highway 115 | 7.3 | | | 1.0 | -0.92 | 0.01 | 3.3 | -2.3 |
| 4W | Quebec | Highway 40 | 7.4 | | | 1.8 | 0.38 | 0.10 | 0.9 | -1.2 |
| 4E | Quebec | Highway 40 | 7.5 | | | 1.8 | -0.35 | -0.08 | 1.0 | -0.9 |
| 1W | Ontario | Highway 417 | 7.6 | | | 0.8 | 0.45 | -0.01 | 1.8 | -2.1 |
| 8W | Quebec | Highway 40 | 11.1 | | | 1.3 | -0.06 | 0.08 | 0.9 | -1.2 |
| 11E | Ontario | Highway 417 | 14.0 | | | n/a | 0.02 | -0.05 | n/a | n/a |
| 10E | Ontario | Highway 417 | 39.9 | | | n/a | -0.05 | -0.02 | n/a | n/a |
| | **Asphalt** | **Weighted Average** | | | | **1.3** | **-0.02** | **-0.008** | **1.6** | **-1.5** |
| 4E | Quebec | Highway 40 | | 3.4 | | 1.3 | -0.35 | -0.08 | 1.0 | -0.9 |
| 4W | Quebec | Highway 40 | | 3.4 | | 1.1 | 0.38 | 0.10 | 0.9 | -1.2 |
| 9NE | Ontario | Highway 115 | | 7.5 | | 1.7 | -0.92 | 0.01 | 3.3 | -2.3 |
| 6N | Quebec | Highway 13 | | 9.3 | | 1.3 | 0.02 | 0.01 | 2.3 | -2.1 |
| 6S | Quebec | Highway 13 | | 9.4 | | 1.2 | -0.01 | 0.00 | 1.8 | -0.9 |
| 7E | Quebec | Highway 440 | | 13.0 | | 1.4 | -0.01 | -0.07 | 2.0 | -2.9 |
| 7W | Quebec | Highway 440 | | 13.3 | | 1.4 | 0.03 | -0.04 | 3.1 | 2.1 |
| 9SW | Ontario | Highway 115 | | 14.4 | | 1.5 | 0.92 | -0.04 | 2.6 | -3.4 |
| 2E | Ontario | Highway 417 | | 38.9 | | 1.1 | 0.01 | -0.04 | 3.2 | -1.9 |
| | **Concrete** | **Weighted Average** | | | | **1.3** | **0.06** | **-0.03** | **2.7** | **-1.6** |
| 5E | Ontario | Highway 401 | | | 19.8 | 0.6 | -0.01 | 0.01 | 0.8 | -1.1 |
| 5W | Ontario | Highway 401 | | | 19.8 | 0.9 | -0.01 | -0.01 | 0.9 | -1.1 |
| | **Comp.** | **Weighted Average** | | | | **0.8** | **-0.01** | **0.0** | **0.9** | **-1.1** |

- International Roughness Index - summer values
- Grades greater than 0.5% were rejected in the mathematical models
- 10E and 11E were sections from previous studies and no IRI data were collected

### Table 3-3 IRI Seasonal Means and Standard Deviations, Sorted by Test Site

| Section | Description | Length | Fall 2002 | Winter 2003 | Spring 2003 | Summer 2003 | Mean | Std Dev |
|---|---|---|---|---|---|---|---|---|
| | | (m) | (m/km) | (m/km) | (m/km) | (m/km) | (m/km) | (m/km) |
| 1E | 417 Eastbound Kanata (Asphalt) | 7663 | 0.97 | 1.10 | 1.02 | 1.05 | 1.04 | 0.05 |
| 1W | 417 Westbound Kanata (Asphalt) | 7696 | 0.82 | 1.12 | 0.86 | 0.87 | 0.92 | 0.14 |
| 2E | 417 Eastbound Casselman (Con.) | 35574 | 1.23 | 1.29 | 1.13 | 1.13 | 1.20 | 0.08 |
| 3E | 40 Eastbound Rigaud (Asphalt) | 3504 | 1.05 | 1.09 | 1.08 | 1.07 | 1.07 | 0.02 |
| 3W | 40 Westbound Rigaud (Asphalt) | 3518 | 1.22 | 2.07 | 1.32 | 1.36 | 1.49 | 0.39 |
| 4E | 40 E Hudson/Vaudreuil (Conc.) | 3400 | 1.61 | 1.76 | 1.68 | 1.77 | 1.69 | 0.06 |
| 4E | 40 E Hudson/Vaudreuil (Asphalt) | 7500 | 1.26 | 1.20 | 1.20 | 1.33 | 1.26 | 0.06 |
| 4W | 40 W Hudson/Vaudreuil (Conc.) | 3400 | 1.71 | 1.92 | 1.85 | 1.78 | 1.82 | 0.09 |
| 4W | 40 W Hudson/Vaudreuil (Asphalt) | 7500 | 1.29 | 1.22 | 1.13 | 1.14 | 1.28 | 0.08 |
| 5E | 401 Eastbound Prescott (Comp) | 20072 | 0.55 | 0.94 | 0.58 | 0.58 | 0.66 | 0.19 |
| 5W | 401 Westbound Prescott (Comp) | 20063 | 0.90 | 1.09 | 1.03 | 1.09 | 1.03 | 0.09 |
| 6N | 13 Northbound Laval (Concrete.) | 9516 | 1.30 | 1.40 | 1.27 | 1.27 | 1.31 | 0.06 |
| 6S | 13 Southbound Laval (Concrete) | 9566 | 1.22 | 1.32 | 1.17 | 1.17 | 1.22 | 0.07 |
| 7E | 440 Eastbound Laval (Concrete) | 13050 | 1.25 | 1.31 | 1.34 | 1.35 | 1.31 | 0.05 |
| 7W | 440 Westbound Laval (Concrete) | 13037 | 1.23 | 1.28 | 1.37 | 1.36 | 1.31 | 0.07 |
| 7N | 25 Northbound Laval (Asphalt) | 2506 | 1.28 | 1.60 | 1.39 | 1.37 | 1.41 | 0.14 |
| 7S | 25 Southbound Laval (Asphalt) | 2498 | 1.36 | 1.81 | 1.39 | 1.42 | 1.50 | 0.21 |
| 8W | 40 Westbound Kirkland (Asphalt) | 8159 | 1.30 | 1.54 | 1.27 | 1.27 | 1.35 | 0.13 |
| 9NE | 115 N Peterborough (Asphalt) | 7300 | 1.03 | 1.20 | 1.04 | 0.98 | 1.04 | 0.09 |
| 9NE | 115 N Peterborough (Concrete) | 7500 | 1.73 | 1.80 | 1.82 | 1.69 | 1.76 | 0.06 |
| 9SW | 115 S Peterborough (Asphalt) | 3100 | 1.46 | 1.55 | 1.44 | 1.48 | 1.49 | 0.05 |
| 9SW | 115 S Peterborough (Concrete) | 14400 | 1.07 | 1.58 | 1.22 | 1.18 | 1.28 | 0.22 |

**Table 3-4 IRI Seasonal Means and Standard Deviations, Sorted by Pavement Type**

| Section | Description | Length (m) | Fall 2002 (m/km) | Winter 2003 (m/km) | Spring 2003 (m/km) | Summer 2003 (m/km) | Mean (m/km) | Std Dev (m/km) |
|---|---|---|---|---|---|---|---|---|
| 7S | 25 Southbound Laval (Asphalt) | 2498 | 1.36 | 1.81 | 1.39 | 1.42 | 1.50 | 0.21 |
| 7N | 25 Northbound Laval (Asphalt) | 2506 | 1.28 | 1.60 | 1.39 | 1.37 | 1.41 | 0.14 |
| 9SW | 115 S Peterborough (Asphalt) | 3100 | 1.46 | 1.55 | 1.44 | 1.48 | 1.49 | 0.05 |
| 3E | 40 Eastbound Rigaud (Asphalt) | 3504 | 1.05 | 1.09 | 1.08 | 1.07 | 1.07 | 0.02 |
| 3W | 40 Westbound Rigaud (Asphalt) | 3518 | 1.22 | 2.07 | 1.32 | 1.36 | 1.49 | 0.39 |
| 9NE | 115 N Peterborough (Asphalt) | 7300 | 1.03 | 1.20 | 1.04 | 0.98 | 1.04 | 0.09 |
| 4E | 40 E Hudson/Vaudreuil (Asphalt) | 7500 | 1.26 | 1.20 | 1.20 | 1.33 | 1.26 | 0.06 |
| 4W | 40 W Hudson/Vaudreuil (Asphalt) | 7500 | 1.29 | 1.22 | 1.13 | 1.14 | 1.28 | 0.08 |
| 1E | 417 Eastbound Kanata (Asphalt) | 7663 | 0.97 | 1.10 | 1.02 | 1.05 | 1.04 | 0.05 |
| 1W | 417 Westbound Kanata (Asphalt) | 7696 | 0.82 | 1.12 | 0.86 | 0.87 | 0.92 | 0.14 |
| 8W | 40 Westbound Kirkland (Asphalt) | 8159 | 1.30 | 1.54 | 1.27 | 1.27 | 1.35 | 0.13 |
| | **Weighted Average Asphalt** | | **1.15** | **1.33** | **1.14** | **1.16** | **1.21** | **0.11** |
| 4E | 40 E Hudson/Vaudreuil (Conc.) | 3400 | 1.61 | 1.76 | 1.68 | 1.77 | 1.69 | 0.06 |
| 4W | 40 W Hudson/Vaudreuil (Conc.) | 3400 | 1.71 | 1.92 | 1.85 | 1.78 | 1.82 | 0.09 |
| 9NE | 115 N Peterborough (Concrete) | 7500 | 1.73 | 1.80 | 1.82 | 1.69 | 1.76 | 0.06 |
| 6N | 13 Northbound Laval (Concrete.) | 9516 | 1.30 | 1.40 | 1.27 | 1.27 | 1.31 | 0.06 |
| 6S | 13 Southbound Laval (Concrete) | 9566 | 1.22 | 1.32 | 1.17 | 1.17 | 1.22 | 0.07 |
| 7W | 440 Westbound Laval (Concrete) | 13037 | 1.23 | 1.28 | 1.37 | 1.36 | 1.31 | 0.07 |
| 7E | 440 Eastbound Laval (Concrete) | 13050 | 1.25 | 1.31 | 1.34 | 1.35 | 1.31 | 0.05 |
| 9SW | 115 S Peterborough (Concrete) | 14400 | 1.07 | 1.58 | 1.22 | 1.18 | 1.28 | 0.22 |
| 2E | 417 Eastbound Casselman (Con.) | 35574 | 1.23 | 1.29 | 1.13 | 1.13 | 1.20 | 0.08 |
| | **Weighted Average Concrete** | | **1.28** | **1.41** | **1.30** | **1.28** | **1.32** | **0.09** |
| 5W | 401 Westbound Prescott (Comp) | 20063 | 0.90 | 1.09 | 1.03 | 1.09 | 1.03 | 0.09 |
| 5E | 401 Eastbound Prescott (Comp) | 20072 | 0.55 | 0.94 | 0.58 | 0.58 | 0.66 | 0.19 |
| | **Weighted Average Composite** | | **0.73** | **1.02** | **0.81** | **0.84** | **0.85** | **0.14** |

## 3.2 Operational Routes

Because of the large geographical area that was covered by the test sites and the operational starting base of the vehicle equipment supplier in Prescott, the sites were grouped into the following three routes (test loops), which allowed for the completion of testing in one working day for each:

Route 1 - Prescott to Montreal - collecting data on Site 5E (401E), Site 6 (Highway 13), Site 7 (Highway 440/25), Site 8 (Highway 40W) and Site 5W (Highway 401W)
.
Route 2 - Prescott to Kanata – collecting data at Site 1 (Highway 417 at Carp) then through to 417 E concrete, 40 Rigaud, Hudson/Vaudreuil and then back to Prescott via Highways 40, 450, 20 and 401.

Route 3 - Prescott to Peterborough via 401/115 and back the same way.

# 4 PHASE III TRACTOR TRAILER RESULTS

As described in Section 3.1, there were a total of 736 individual test data files collected. The following section summarizes the results of the data analysis.

## 4.1 Error Analysis and Test Repeatability

The published error rates for the instruments used to collect the data were as follows:

Anemometer, Wind Speed: +/- 1%
Anemometer, Wind Direction: +/- 5%
Cummins Data Acquisition System: +/- 1%
GPS accuracy: +/- 2 cm to local station, +/- 50 cm to global co-ordinate system.
IRI accuracy: +/- 0.5%

To ensure an appropriate level of test repeatability, the physical test site locations and test conditions were carefully defined and controlled throughout the test program. In addition, the operation of the truck and the accuracy and repeatability of the fuel use measurement was tracked throughout the project. The principal control measure for season to season changes in fuel flow measurement accuracy was through the comparison of the fuel used on a test day trip set between the fill-up at the depot and the engine fuel use information. Since testing was performed on a seasonal basis, there was no need for a diesel fuel temperature/volumetric adjustment. Short ‘loop-around’ road courses were utilized, as much as possible, to minimize the effects of tail and head winds. A wind speed anemometer was used in order to compensate for slight variations in head and tail wind. The anemometer was located well ahead of the tractor’s pressure zone (as per SAE standards) in order to detect the true ambient wind speed and direction. These data were collected in the same time domain as the fuel burn data, allowing the data analysts to remove the wind’s effects from the vehicle’s fuel consumption.

In addition, periodic repeatability trials were performed in which the vehicle was driven twice over the same section of road, at the same speed, load and climatic conditions. Sample data from one such test are presented at Figure 4-1 and indicate high repeatability, for that particular test, with a 0.02% difference in the average fuel consumption rates between the two runs.

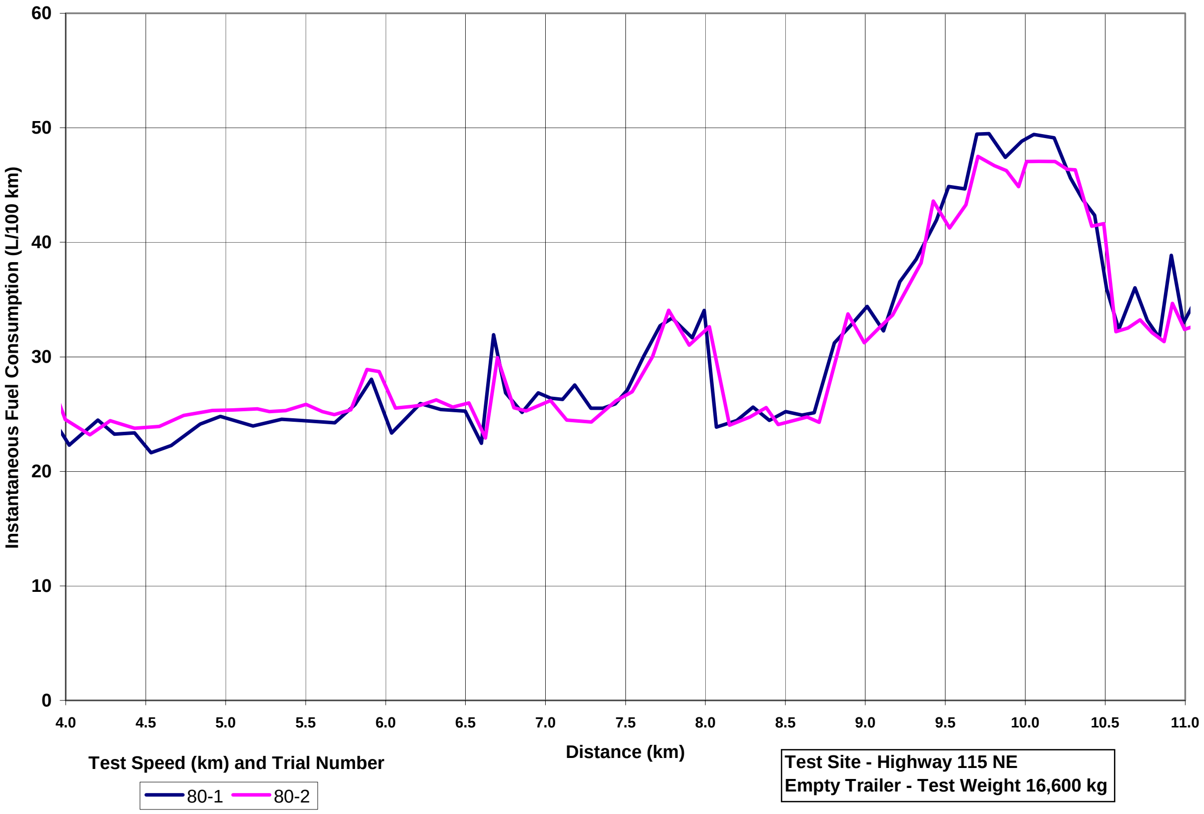

**Figure 4-1 Repeatability of Instantaneous Fuel Consumption Over a Test Course**

## 4.2 Test Data Processing

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.

## 4.3 Pavement Flexibility and Strength Tests

As presented in section 2.5, the strength of the road was measured using a Falling Weight Deflectometer test. The results of those tests may be found in Appendix B. However, it should be noted that the effect of road strength was not an important variable in the mathematical analysis as the road beds used in this study were all of similar construction and quality. This is not to say that road strength is not a factor in fuel efficiency, but rather, the roads used in this study were all constructed using similar techniques and therefore these data became insignificant for the purposes of the Phase III model.

## 4.4 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. Pavement structure was 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.

The following statistical terms are defined as:

> **$t_{ratio}$:** This is the test statistic from which is computed the $P_{value}$. T ratio is dimension-less and for the purposes of this study was defined as: Coef/SE Coef
>
> **$P_{value}$:** Probability value, or the smallest value of significance (e.g. 5%) that would lead to the rejection of a hypothesis**.** It provides an objective assessment of the validity of a hypothesis. If the $P_{value}$ is less than a chosen level of significance, the hypothesis is rejected. Otherwise, the hypothesis is accepted.

Tables 4-1 through 4-6 provide the individual season model results for the truck and trailer and include the sample size, variable coefficients, statistical measures of variable significance, statistical measures of variable error and overall correlation. All the seasonal models had strong coefficients of determination ($R^2$) values ranging between 65% and 79%. Given the large number of records in the results database, these are very good modelling results. As an example, the p-value reported in the last column of row 2 in Table 4-1 shows a value of 0.002. This indicates that in only 0.2% of the time would a value larger than 0.4327 occur (Pvash).

**Table 4-1 Truck Winter Model**

| **Predictor** | **Coef** | **SE Coef** | **$t_{ratio}$** | **$P_{value}$** |
|---|---|---|---|---|
| Constant | -17.6131 | 0.6102 | -28.87 | 0 |
| Pvash | 0.4327 | 0.1363 | 3.18 | 0.002 |
| Pvcomp | 0.7368 | 0.2065 | 3.57 | 0 |
| IRI | 0.6487 | 0.2016 | 3.22 | 0.001 |
| Grade | 11.2539 | 0.1474 | 76.35 | 0 |
| Load | 0.000118 | 1.95E-06 | 60.46 | 0 |
| Pavetemp | -0.20758 | 0.01425 | -14.57 | 0 |
| Speed | 0.34515 | 0.01069 | 32.28 | 0 |
| AirSpdSq | 0.001794 | 7.02E-05 | 25.55 | 0 |
| 10,049 observations $R^2$ = 78.9% | | | | |

### Table 4-2 Truck Spring Model

| Predictor | Coef | SE Coef | $t_{ratio}$ | $P_{value}$ |
|---|---|---|---|---|
| Constant | -15.2602 | 0.5269 | -28.96 | 0 |
| Pvash | 0.68197 | 0.09632 | 7.08 | 0 |
| Pvcomp | 0.3626 | 0.1879 | 1.93 | 0.054 |
| IRI | 0.8978 | 0.1545 | 5.81 | 0 |
| Grade | 16.8042 | 0.1169 | 143.76 | 0 |
| Load | 7.76E-05 | 2.26E-06 | 34.28 | 0 |
| Pavetemp | -0.00556 | 0.02621 | -0.21 | 0.832 |
| Speed | 0.370659 | 0.008395 | 44.15 | 0 |
| AirSpdSq | 0.001414 | 5.42E-05 | 26.12 | 0 |
| 34,572 observations $R^2$ = 65.5% | | | | |

### Table 4-3 Truck Summer Day Model

| Predictor | Coef | SE Coef | $t_{ratio}$ | $P_{value}$ |
|---|---|---|---|---|
| Constant | -17.456 | 1.199 | -14.56 | 0 |
| Pvash | 0.6118 | 0.1439 | 4.25 | 0 |
| Pvcomp | -0.5495 | 0.2088 | -2.63 | 0.009 |
| IRI | 0.4758 | 0.2257 | 2.11 | 0.035 |
| Grade | 15.6395 | 0.1645 | 95.08 | 0 |
| Load | 8.74E-05 | 2.1E-06 | 41.68 | 0 |
| Pavetemp | 0.20555 | 0.02844 | 7.23 | 0 |
| Speed | 0.27921 | 0.008845 | 31.57 | 0 |
| AirSpdSq | 0.001437 | 5.43E-05 | 26.44 | 0 |
| 12,802 observations $R^2$ = 68.1% | | | | |

### Table 4-4 Truck Summer Night Model

| Predictor | Coef | SE Coef | $t_{ratio}$ | $P_{value}$ |
|---|---|---|---|---|
| Constant | -2.8886 | 0.772 | -3.74 | 0 |
| Pvash | 0.1662 | 0.1296 | 1.28 | 0.2 |
| Pvcomp | 0.8441 | 0.2118 | 3.99 | 0 |
| IRI | 0.2412 | 0.2092 | 1.15 | 0.249 |
| Grade | 15.4992 | 0.1475 | 105.1 | 0 |
| Load | 1.98E-05 | 7E-07 | 28.45 | 0 |
| Pavetemp | -0.15004 | 0.01932 | -7.76 | 0 |
| Speed | 0.30356 | 0.01247 | 24.34 | 0 |
| AirSpdSq | 0.001372 | 8.33E-05 | 16.47 | 0 |
| 14,266 observations $R^2$ = 69.9% | | | | |

### Table 4-5 Truck Fall Model

| Predictor | Coef | SE Coef | $t_{ratio}$ | $P_{value}$ |
|---|---|---|---|---|
| Constant | -14.3128 | 0.6039 | -23.7 | 0 |
| Pvash | 0.3945 | 0.1397 | 2.82 | 0.005 |
| Pvcomp | 1.1959 | 0.2186 | 5.47 | 0 |
| IRI | 1.3243 | 0.2148 | 6.17 | 0 |
| Grade | 12.4083 | 0.1581 | 78.51 | 0 |
| Load | 0.000121 | 2.76E-06 | 43.59 | 0 |
| Pavetemp | 0.08106 | 0.0335 | 2.42 | 0.016 |
| Speed | 0.30545 | 0.01122 | 27.22 | 0 |
| AirSpdSq | 0.00171 | 7.59E-05 | 22.55 | 0 |
| 9,460 observations $R^2$ = 76.3% | | | | |

### Table 4-6 Truck All-season Model

| Predictor | Coef | SE Coef | $t_{ratio}$ | $P_{value}$ |
|---|---|---|---|---|
| Constant | -8.6187 | 0.2487 | -34.66 | 0 |
| Pvash | 0.55406 | 0.05838 | 9.49 | 0 |
| Pvcomp | 0.14143 | 0.09747 | 1.45 | 0.147 |
| IRI | 0.5741 | 0.09187 | 6.25 | 0 |
| Grade | 15.1716 | 0.0694 | 218.55 | 0 |
| Load | 4.39E-05 | 6.1E-07 | 71.52 | 0 |
| Pavetemp | -0.07563 | 0.00169 | -44.75 | 0 |
| Speed | 0.337456 | 0.004679 | 72.12 | 0 |
| AirSpdSq | 0.001444 | 3.02E-05 | 47.74 | 0 |
| 81,150 observations $R^2$ = 67.1% | | | | |

## 4.5 Analysis of Point Estimates

In order to quantify and compare the savings in fuel consumption on concrete relative to asphalt or composite pavements, point estimates and confidence bounds were determined for expected fuel consumption on each surface for a range of temperatures in each seasonal model.

Calculations were performed using the following assumptions:

- an IRI of 1.0 to reflect a relatively smooth surface;
- percent grade of 0;
- speed of 100 km/h;
- loads of 16,000 (“empty”), 43,660 (“full”), and 49,400 kg (“max”); and
- relative wind speed of 0 km/h.

For the purposes of data analysis, rougher roads were not considered as part of Phase III. Earlier models, from previous phases, indicated that surface roughness was a significant factor contributing to fuel consumption (i.e. the greater the road roughness, the greater the amount of fuel burned per distance travelled).

The estimates derived from each seasonal model for the empty and full loads at 100 km/h are provided in Tables 4-7 through 4-18. Each table gives point estimates, as well as 95% confidence bounds for expected fuel consumption for trucks on smooth road surfaces. Further, for each ambient temperature, the point estimates for expected fuel consumption were used to compute a percentage change in fuel consumption when driving on asphalt relative to concrete and composite relative to concrete.

The differences in fuel consumption rate between asphalt and concrete were equal to the coefficient of Pvash itself. The differences in fuel consumption rate between composite and concrete were equal to the coefficient of Pvcomp itself. An example of this is illustrated below, where Pvash is equal to 0.4327 (Table 4-1):

If the absolute fuel consumption rate, denoted $fc$, were known exactly, the 95 % confidence interval, denoted $CI$, for the percent difference would be:

$$\left[\frac{Lower95\%CI}{fc},\frac{Upper95\%CI}{fc}\right]$$

where $\left[Lower95\%CI, Upper95\%CI\right]$ represents the 95% confidence interval for the difference itself. Hence, for example, for the full winter model when the PaveTemp is –15, the difference is equal to Pvash = 0.4327, and the SE Coef is equal to 0.1363 (Table 4-1), for which the 95% confidence interval is:

$$[0.4327 - 1.96\ (0.1363),\ 0.4327 + 1.96\ (0.1363)]$$

$$= [0.17,\ 0.70]$$

The estimate for concrete is equal to $fc$ = 49.9. Hence, if the absolute fuel consumption rate were known exactly, the 95 % confidence interval for the percent difference would be:

[0.17/49.9, 0.70/49.9] = [0.34%, 1.40%].

Unfortunately, the rate $fc$ is not known exactly and a 95% confidence interval for it is obtained from Table 4-7 as [49.6, 50.2].

[0.17/50.2, 0.70/49.6] = [0.34%, 1.41%].

In order to compute a 95% confidence interval it is necessary to combine two confidence intervals into a single probability statement by making use of the Bonferroni inequality. This requires the construction of 97.5 % confidence intervals for each of the numerator and denominator. This, in turn, would require a cutoff value equal to 2.24 be used, instead of 1.96, in the various calculations.

By way of example, 97.5% confidence intervals were calculated for the percentage difference as well as for the absolute fuel consumption using concrete, using the example calculations shown above. This yielded the intervals [0.1274, 0.7380] [49.557, 50.243] respectively. Hence, an overall 95% confidence interval for the percentage difference becomes:

[0.1274/50.243, 0.7380/49.557] = [0.25 %, 1.49%].

Therefore, there is a 95% probability that, under the conditions specified above, the test truck would have burned between 0.25% and 1.49% less fuel on concrete roads, when compared to the asphalt roads. Since zero is not contained within this interval, the result is considered statistically significant. Conversely, if the two values had spanned 0% (e.g. [-0.25%, 1.49%]), the results would be considered not statistically significant. Tables 4-7 through 4-18 illustrate all the 95% confidence intervals over the various road and weather conditions and whether or not each result is significant or not significant (calculated using the combined 97.5% intervals). Shaded cells represent results that have been computed to be not statistically significant.

A graphical presentation of the point concrete road estimates for all the seasonal models and load conditions is shown in Figure 4-2. The asphalt and composite plots are similar but offset by their model coefficients. Note that the Spring model data has been excluded from the graph as the data points are very close to the Fall data and as the temperature differentials in the Spring data were small there is very low sensitivity in the model to temperature.

The point estimates for each seasonal model and the combined all season model for a “full” (43,660 kg) load condition and 100 km/h are illustrated in Figure 4-3 and clearly show that across all the seasonal models, the sensitivity to ambient temperature is higher using the seasonal models. Further, the seasonal models have higher coefficients of determination for the multiple regression models and thus are better models. Finally, the slopes of the temperature sensitivity are not consistent among the seasonal models with the Fall and Summer Day models indicating a positive slope and the Winter and Spring (and Summer Night although not plotted on the graph) had negative slopes. Even with these anomalies, the model clearly indicates that the effect of temperature far outweighs the effect of the pavement types, both within each season and across the total temperature range that was tested.

As a further example of the model’s sensitivity, Table 4-19 presents the estimates across the complete temperature range at the test speed of 60 km/h with no load (16,000 kg). The estimates indicate a 0.25 L/100km difference between concrete and composite which is not statistically significant at the 95th percentile confidence bound and a 0.55 L/100km difference between concrete and asphalt which was computed to be statistically significant.

**Table 4-7 Full, Winter Point Estimates, 100km/h,IRI =1.0,pavement temps= –20,–15, & –10$^{o}$ C**

| Pave Temp | Surface | Estimate | 95 Lower | 95 Upper | 97.5 Lower | 97.5 Upper | Absolute Diff (low) L/100km | Absolute Diff (High) L/100km | Percent Diff (low) | Percent Diff (high) |
|---|---|---|---|---|---|---|---|---|---|---|
| -10 | Asphalt | 49.3 | 48.9 | 49.6 | 48.9 | 49.7 | 0.1 | 0.7 | 0.3% | 1.5% |
| -15 | Asphalt | 50.3 | 50.0 | 50.6 | 50.0 | 50.7 | 0.1 | 0.7 | 0.3% | 1.5% |
| -20 | Asphalt | 51.4 | 51.0 | 51.7 | 51.0 | 51.8 | 0.1 | 0.7 | 0.2% | 1.5% |
| -10 | Composite | 49.6 | 49.2 | 49.9 | 49.2 | 50.0 | 0.3 | 1.2 | 0.6% | 2.5% |
| -15 | Composite | 50.6 | 50.3 | 50.9 | 50.3 | 51.0 | 0.3 | 1.2 | 0.5% | 2.4% |
| -20 | Composite | 51.7 | 51.3 | 52.0 | 51.3 | 52.1 | 0.3 | 1.2 | 0.5% | 2.4% |
| -10 | Concrete | 48.9 | 48.5 | 49.2 | 48.5 | 49.3 | | | | |
| -15 | Concrete | 49.9 | 49.6 | 50.2 | 49.6 | 50.2 | | | | |
| -20 | Concrete | 50.9 | 50.6 | 51.3 | 50.5 | 51.3 | | | | |

**Table 4-8 Full, Spring Point Estimates (100km/h,IRI =1.0,pavement temps = 10,15,& 20$^{o}$ C)**

| Pave Temp | Surface | Estimate | 95 Lower | 95 Upper | 97.5 Lower | 97.5 Upper | Absolute Diff (low) L/100km | Absolute Diff (High) L/100km | Percent Diff (low) | Percent Diff (high) |
|---|---|---|---|---|---|---|---|---|---|---|
| 20 | Asphalt | 44.9 | 44.5 | 45.3 | 44.4 | 45.3 | 0.5 | 0.9 | 1.0% | 2.1% |
| 15 | Asphalt | 44.9 | 44.7 | 45.1 | 44.7 | 45.1 | 0.5 | 0.9 | 1.0% | 2.0% |
| 10 | Asphalt | 44.9 | 44.6 | 45.2 | 44.6 | 45.3 | 0.5 | 0.9 | 1.0% | 2.0% |
| 20 | Composite | 44.5 | 44.1 | 44.9 | 44.1 | 45.0 | -0.1 | 0.8 | -0.1% | 1.8% |
| 15 | Composite | 44.6 | 44.4 | 44.8 | 44.3 | 44.8 | -0.1 | 0.8 | -0.1% | 1.8% |
| 10 | Composite | 44.6 | 44.3 | 44.9 | 44.3 | 44.9 | -0.1 | 0.8 | -0.1% | 1.8% |
| 20 | Concrete | 44.2 | 43.8 | 44.6 | 43.7 | 44.6 | | | | |
| 15 | Concrete | 44.2 | 44.0 | 44.4 | 44.0 | 44.4 | | | | |
| 10 | Concrete | 44.2 | 43.9 | 44.5 | 43.9 | 44.6 | | | | |

Shaded cells indicate fuel consumption differences that are not statistically significant

**Table 4-9 Full, Summer Day Point Estimates, 100km/h, IRI =1.0, pavement temps = 25, 30 & 35$^o$ C**

| Pave Temp | Surface | Estimate | 95 Lower | 95 Upper | 97.5 Lower | 97.5 Upper | Absolute Diff (low) L/100km | Absolute Diff (High) L/100km | Percent Diff (low) | Percent Diff (high) |
|---|---|---|---|---|---|---|---|---|---|---|
| 35 | Asphalt | 41.5 | 41.1 | 41.8 | 41.1 | 41.9 | 0.3 | 0.9 | 0.7% | 2.3% |
| 30 | Asphalt | 40.4 | 39.9 | 41.0 | 39.8 | 41.0 | 0.3 | 0.9 | 0.7% | 2.4% |
| 25 | Asphalt | 39.4 | 38.6 | 40.1 | 38.5 | 40.2 | 0.3 | 0.9 | 0.7% | 2.5% |
| 35 | Composite | 40.3 | 39.9 | 40.6 | 39.9 | 40.7 | -1.0 | -0.1 | -2.5% | -0.2% |
| 30 | Composite | 39.3 | 38.7 | 39.8 | 38.6 | 39.9 | -1.0 | -0.1 | -2.5% | -0.2% |
| 25 | Composite | 38.2 | 37.5 | 39.0 | 37.4 | 39.1 | -1.0 | -0.1 | -2.6% | -0.2% |
| 35 | Concrete | 40.8 | 40.5 | 41.2 | 40.4 | 41.2 | | | | |
| 30 | Concrete | 39.8 | 39.3 | 40.4 | 39.2 | 40.4 | | | | |
| 25 | Concrete | 38.8 | 38.1 | 39.6 | 37.9 | 39.6 | | | | |

**Table 4-10 Full, Summer Night Point Estimates, 100km/h, IRI =1.0, pavement temps = 20, 25 & 30$^o$ C**

| Pave Temp | Surface | Estimate | 95 Lower | 95 Upper | 97.5 Lower | 97.5 Upper | Absolute Diff (low) L/100km | Absolute Diff (High) L/100km | Percent Diff (low) | Percent Diff (high) |
|---|---|---|---|---|---|---|---|---|---|---|
| 30 | Asphalt | 39.0 | 38.6 | 39.5 | 38.5 | 39.5 | -0.1 | 0.5 | -0.3% | 1.2% |
| 25 | Asphalt | 39.7 | 39.4 | 40.1 | 39.3 | 40.1 | -0.1 | 0.5 | -0.3% | 1.2% |
| 20 | Asphalt | 40.5 | 40.2 | 40.9 | 40.1 | 40.9 | -0.1 | 0.5 | -0.3% | 1.1% |
| 30 | Composite | 39.7 | 39.3 | 40.2 | 39.2 | 40.2 | 0.4 | 1.3 | 0.9% | 3.4% |
| 25 | Composite | 40.4 | 40.1 | 40.8 | 40.0 | 40.8 | 0.4 | 1.3 | 0.9% | 3.4% |
| 20 | Composite | 41.2 | 40.9 | 41.6 | 40.8 | 41.6 | 0.4 | 1.3 | 0.9% | 3.3% |
| 30 | Concrete | 38.8 | 38.4 | 39.3 | 38.3 | 39.3 | | | | |
| 25 | Concrete | 39.6 | 39.2 | 39.9 | 39.2 | 40.0 | | | | |
| 20 | Concrete | 40.3 | 40.0 | 40.7 | 39.9 | 40.7 | | | | |

Shaded cells indicate fuel consumption differences that are not statistically significant

**Table 4-11 Full, Fall Point Estimates, 100km/h, IRI =1.0, pavement temps = -5, 0 & +5$^{o}$ C**

| Pave Temp | Surface | Estimate | 95 Lower | 95 Upper | 97.5 Lower | 97.5 Upper | Absolute Diff (low) L/100km | Absolute Diff (High) L/100km | Percent Diff (low) | Percent Diff (high) |
|---|---|---|---|---|---|---|---|---|---|---|
| 5 | Asphalt | 47.0 | 46.4 | 47.7 | 46.3 | 47.8 | 0.1 | 0.7 | 0.2% | 1.5% |
| 0 | Asphalt | 46.6 | 46.2 | 47.1 | 46.1 | 47.1 | 0.1 | 0.7 | 0.2% | 1.5% |
| -5 | Asphalt | 46.2 | 45.9 | 46.6 | 45.8 | 46.6 | 0.1 | 0.7 | 0.2% | 1.6% |
| 5 | Composite | 47.8 | 47.2 | 48.5 | 47.1 | 47.8 | 0.7 | 1.7 | 1.5% | 3.7% |
| 0 | Composite | 47.4 | 47.0 | 47.9 | 46.9 | 47.4 | 0.7 | 1.7 | 1.5% | 3.7% |
| -5 | Composite | 47.0 | 46.7 | 47.4 | 46.6 | 47.0 | 0.7 | 1.7 | 1.5% | 3.7% |
| 5 | Concrete | 46.6 | 46.0 | 47.3 | 45.9 | 47.4 | | | | |
| 0 | Concrete | 46.2 | 45.8 | 46.7 | 45.7 | 46.8 | | | | |
| -5 | Concrete | 45.8 | 45.5 | 46.2 | 45.4 | 46.2 | | | | |

**Table 4-12 Full, All data Model Point Estimates (Speed=100, IRI =1.0)**

| Pave Temp | Surface | Estimate | 95 Lower | 95 Upper | 97.5 Lower | 97.5 Upper | Absolute Diff (low) L/100km | Absolute Diff (High) L/100km | Percent Diff (low) | Percent Diff (high) |
|---|---|---|---|---|---|---|---|---|---|---|
| 35 | Asphalt | 42.3 | 42.2 | 42.5 | 42.1 | 42.5 | 0.4 | 0.7 | 1.0% | 1.6% |
| 25 | Asphalt | 43.0 | 42.9 | 43.2 | 42.8 | 43.2 | 0.4 | 0.7 | 1.0% | 1.6% |
| 15 | Asphalt | 43.8 | 43.7 | 44.0 | 43.6 | 44.0 | 0.4 | 0.7 | 1.0% | 1.6% |
| 0 | Asphalt | 44.9 | 44.8 | 45.1 | 44.7 | 45.1 | 0.4 | 0.7 | 0.9% | 1.5% |
| -15 | Asphalt | 46.0 | 45.8 | 46.2 | 45.8 | 46.2 | 0.4 | 0.7 | 0.9% | 1.5% |
| 35 | Composite | 41.8 | 41.7 | 42.0 | 41.6 | 41.8 | -0.1 | 0.4 | -0.2% | 0.9% |
| 25 | Composite | 42.6 | 42.5 | 42.8 | 42.4 | 42.6 | -0.1 | 0.4 | -0.2% | 0.8% |
| 15 | Composite | 43.4 | 43.3 | 43.6 | 43.2 | 43.4 | -0.1 | 0.4 | -0.2% | 0.8% |
| 0 | Composite | 44.5 | 44.4 | 44.7 | 44.3 | 44.5 | -0.1 | 0.4 | -0.2% | 0.8% |
| -15 | Composite | 45.6 | 45.4 | 45.8 | 45.4 | 45.6 | -0.1 | 0.4 | -0.2% | 0.8% |
| 35 | Concrete | 41.7 | 41.6 | 41.9 | 41.5 | 41.9 | | | | |
| 25 | Concrete | 42.5 | 42.3 | 42.6 | 42.3 | 42.7 | | | | |
| 15 | Concrete | 43.2 | 43.1 | 43.4 | 43.0 | 43.4 | | | | |
| 0 | Concrete | 44.4 | 44.2 | 44.5 | 44.2 | 44.6 | | | | |
| -15 | Concrete | 45.5 | 45.3 | 45.7 | | | | | | |

## Table 4-13 Empty,Winter Point Estimates,100km/h,IRI =1.0,pavement temp= -20,-15,& -10$^{o}$ C

| Pave Temp | Surface | Estimate | 95 Lower | 95 Upper | 97.5 Lower | 97.5 Upper | Absolute Diff (low) L/100km | Absolute Diff (High) L/100km | Percent Diff (low) | Percent Diff (high) |
|---|---|---|---|---|---|---|---|---|---|---|
| -10 | Asphalt | 42.3 | 41.9 | 42.6 | 41.9 | 42.7 | 0.1 | 0.7 | 0.3% | 1.8% |
| -15 | Asphalt | 43.3 | 43.0 | 43.6 | 43.0 | 43.7 | 0.1 | 0.7 | 0.3% | 1.7% |
| -20 | Asphalt | 44.3 | 44.0 | 44.7 | 43.9 | 44.7 | 0.1 | 0.7 | 0.3% | 1.7% |
| -10 | Composite | 42.6 | 42.2 | 42.9 | 42.2 | 43.0 | 0.3 | 1.2 | 0.6% | 2.9% |
| -15 | Composite | 43.6 | 43.3 | 43.9 | 43.3 | 44.0 | 0.3 | 1.2 | 0.6% | 2.8% |
| -20 | Composite | 44.7 | 44.3 | 45.0 | 44.3 | 45.1 | 0.3 | 1.2 | 0.6% | 2.8% |
| -10 | Concrete | 41.8 | 41.5 | 42.20 | 41.4 | 42.2 | | | | |
| -15 | Concrete | 42.9 | 42.60 | 43.20 | 42.5 | 43.2 | | | | |
| -20 | Concrete | 43.9 | 43.6 | 44.30 | 43.5 | 44.3 | | | | |

## Table 4-14 Empty, Spring Point Estimates,100km/h,IRI =1.0,pavement temps =10,15, & 20$^{o}$ C

| Pave Temp | Surface | Estimate | 95 Lower | 95 Upper | 97.5 Lower | 97.5 Upper | Absolute Diff (low) L/100km | Absolute Diff (High) L/100km | Percent Diff (low) | Percent Diff (high) |
|---|---|---|---|---|---|---|---|---|---|---|
| 10 | Asphalt | 40.2 | 39.7 | 40.8 | 39.6 | 40.8 | 0.5 | 0.9 | 1.2% | 2.3% |
| 15 | Asphalt | 40.2 | 39.8 | 40.6 | 39.8 | 40.7 | 0.5 | 0.9 | 1.2% | 2.3% |
| 20 | Asphalt | 40.3 | 39.9 | 40.6 | 39.9 | 40.7 | 0.5 | 0.9 | 1.2% | 2.3% |
| 10 | Composite | 39.9 | 39.3 | 40.4 | 39.3 | 40.5 | -0.1 | 0.8 | -0.1% | 2.0% |
| 15 | Composite | 39.9 | 39.5 | 40.3 | 39.5 | 40.4 | -0.1 | 0.8 | -0.1% | 2.0% |
| 20 | Composite | 40.0 | 39.6 | 40.3 | 39.6 | 40.4 | -0.1 | 0.8 | -0.1% | 2.0% |
| 10 | Concrete | 39.6 | 39.0 | 40.1 | 39.0 | 40.2 | | | | |
| 15 | Concrete | 39.6 | 39.2 | 40.0 | 39.1 | 40.1 | | | | |
| 20 | Concrete | 39.6 | 39.3 | 40.0 | 39.2 | 40.0 | | | | |

Shaded cells indicate fuel consumption differences that are not statistically significant

### Table 4-15 Empty, Summer Day Point Estimates, 100km/h, IRI =1.0, pavement temps = 25, 30, & $35^{o}$ C

| Pave Temp | Surface | Estimate | 95 Lower | 95 Upper | 97.5 Lower | 97.5 Upper | Absolute Diff (low) L/100km | Absolute Diff (High) L/100km | Percent Diff (low) | Percent Diff (high) |
|---|---|---|---|---|---|---|---|---|---|---|
| 35 | Asphalt | 36.3 | 35.9 | 36.7 | 35.8 | 36.7 | 0.3 | 0.9 | 0.8% | 2.7% |
| 30 | Asphalt | 35.2 | 34.7 | 35.8 | 34.6 | 35.9 | 0.3 | 0.9 | 0.8% | 2.7% |
| 25 | Asphalt | 34.2 | 33.4 | 35.0 | 33.3 | 35.1 | 0.3 | 0.9 | 0.8% | 2.9% |
| 35 | Composite | 35.1 | 34.7 | 35.5 | 34.7 | 35.6 | -1.0 | -0.1 | -2.8% | -0.2% |
| 30 | Composite | 34.1 | 33.5 | 34.6 | 33.5 | 34.7 | -1.0 | -0.1 | -2.9% | -0.2% |
| 25 | Composite | 33.1 | 32.3 | 33.9 | 32.1 | 34.0 | -1.0 | -0.1 | -2.9% | -0.2% |
| 35 | Concrete | 35.7 | 35.3 | 36.1 | 35.2 | 36.1 | | | | |
| 30 | Concrete | 34.6 | 34.1 | 35.2 | 34.0 | 35.3 | | | | |
| 25 | Concrete | 33.6 | 32.8 | 34.4 | 32.7 | 34.5 | | | | |

### Table 4-16 Empty, Summer Night Point Estimates, 100km/h, IRI =1.0, pavement temps = 20, 25, & $30^{o}$ C

| Pave Temp | Surface | Estimate | 95 Lower | 95 Upper | 97.5 Lower | 97.5 Upper | Absolute Diff (low) L/100km | Absolute Diff (High) L/100km | Percent Diff (low) | Percent Diff (high) |
|---|---|---|---|---|---|---|---|---|---|---|
| 30 | Asphalt | 37.8 | 37.4 | 38.3 | 37.3 | 38.3 | -0.1 | 0.5 | -0.3% | 1.2% |
| 25 | Asphalt | 38.6 | 38.3 | 39.0 | 38.2 | 39.0 | -0.1 | 0.5 | -0.3% | 1.2% |
| 20 | Asphalt | 39.3 | 38.9 | 39.7 | 38.8 | 39.8 | -0.1 | 0.5 | -0.3% | 1.2% |
| 30 | Composite | 38.6 | 38.1 | 39.0 | 38.0 | 39.1 | 0.4 | 1.3 | 1.0% | 3.6% |
| 25 | Composite | 39.2 | 38.9 | 39.6 | 38.8 | 39.6 | 0.4 | 1.3 | 0.9% | 3.4% |
| 20 | Composite | 40.0 | 39.6 | 40.4 | 39.5 | 40.5 | 0.4 | 1.3 | 1.0% | 3.5% |
| 30 | Concrete | 37.6 | 37.2 | 38.1 | 37.1 | 38.1 | | | | |
| 25 | Concrete | 39.1 | 38.8 | 39.5 | 38.7 | 39.5 | | | | |
| 20 | Concrete | 38.4 | 38.0 | 38.8 | 37.9 | 38.9 | | | | |

Shaded cells indicate fuel consumption differences that are not statistically significant

### Table 4-17 Empty, Fall Point Estimates, 100km/h, IRI =1.0, pavement temps = -5, 0 & +5$^o$ C

| PaveTemp | Surface | Estimate | 95 Lower | 95 Upper | 97.5 Lower | 97.5 Upper | Absolute Diff (low) L/100km | Absolute Diff (High) L/100km | Percent Diff (low) | Percent Diff (high) |
|---|---|---|---|---|---|---|---|---|---|---|
| 5 | Asphalt | 39.8 | 39.3 | 40.3 | 39.3 | 40.4 | 0.1 | 0.7 | 0.2% | 1.8% |
| 0 | Asphalt | 39.4 | 39.0 | 39.9 | 38.9 | 39.9 | 0.1 | 0.7 | 0.2% | 1.9% |
| -5 | Asphalt | 39.0 | 38.7 | 39.4 | 38.6 | 39.4 | 0.1 | 0.7 | 0.2% | 1.8% |
| 5 | Composite | 40.6 | 40.1 | 41.1 | 40.1 | 41.2 | 0.7 | 1.7 | 1.8% | 4.3% |
| 0 | Composite | 40.2 | 39.8 | 40.7 | 39.7 | 40.8 | 0.7 | 1.7 | 1.8% | 4.4% |
| -5 | Composite | 39.8 | 39.5 | 40.2 | 39.4 | 40.2 | 0.7 | 1.7 | 1.8% | 4.3% |
| 5 | Concrete | 39.5 | 39.0 | 40.0 | 38.9 | 40.1 | | | | |
| 0 | Concrete | 38.7 | 38.2 | 39.1 | 38.2 | 39.2 | | | | |
| -5 | Concrete | 39.1 | 38.7 | 39.4 | 38.7 | 39.5 | | | | |

### Table 4-18 Empty, All data Model Point Estimates (Speed=100, IRI =1.0)

| PaveTemp | Surface | Estimate | 95 Lower | 95 Upper | 97.5 Lower | 97.5 Upper | Absolute Diff (low) L/100km | Absolute Diff (High) L/100km | Percent Diff (low) | Percent Diff (high) |
|---|---|---|---|---|---|---|---|---|---|---|
| 35 | Asphalt | 39.6 | 39.4 | 39.8 | 39.4 | 39.8 | 0.4 | 0.7 | 1.1% | 1.8% |
| 25 | Asphalt | 40.4 | 40.3 | 40.6 | 40.2 | 40.6 | 0.4 | 0.7 | 1.1% | 1.7% |
| 15 | Asphalt | 41.2 | 41.1 | 41.4 | 41.0 | 41.4 | 0.4 | 0.7 | 1.0% | 1.7% |
| 0 | Asphalt | 42.3 | 42.2 | 42.5 | 42.1 | 42.5 | 0.4 | 0.7 | 1.0% | 1.6% |
| -15 | Asphalt | 43.4 | 43.3 | 43.6 | 43.2 | 43.6 | 0.4 | 0.7 | 1.0% | 1.6% |
| 35 | Composite | 39.2 | 39.0 | 39.4 | 39.0 | 39.4 | -0.1 | 0.4 | -0.2% | 0.9% |
| 25 | Composite | 40.0 | 39.9 | 40.2 | 39.8 | 40.2 | -0.1 | 0.4 | -0.2% | 0.9% |
| 15 | Composite | 40.7 | 40.6 | 40.9 | 40.5 | 40.9 | -0.1 | 0.4 | -0.2% | 0.9% |
| 0 | Composite | 41.9 | 41.8 | 42.1 | 41.7 | 42.1 | -0.1 | 0.4 | -0.2% | 0.9% |
| -15 | Composite | 43.0 | 42.9 | 43.2 | 42.8 | 43.2 | -0.1 | 0.4 | -0.2% | 0.8% |
| 35 | Concrete | 39.1 | 38.9 | 39.3 | 38.9 | 39.3 | | | | |
| 25 | Concrete | 39.9 | 39.7 | 40 | 39.7 | 40.1 | | | | |
| 15 | Concrete | 40.6 | 40.5 | 40.8 | 40.4 | 40.8 | | | | |
| 0 | Concrete | 41.7 | 41.6 | 41.9 | 41.5 | 41.9 | | | | |
| -15 | Concrete | 42.9 | 42.7 | 43 | 42.7 | 43.1 | | | | |

Shaded cells indicate fuel consumption differences that are not statistically significant

**Table 4-19 Empty, All Data Model Point Estimates (IRI = 1.0, Speed = 60 km/h)**

| Pave Temp | Surface | Estimate | 95 Lower | 95 Upper | 97.5 Lower | 97.5 Upper | Absolute Diff (low) L/100km | Absolute Diff (High) L/100km | Percent Diff (low) | Percent Diff (high) |
|---|---|---|---|---|---|---|---|---|---|---|
| 35 | Asphalt | 19.2 | 19.0 | 19.4 | 19.0 | 19.4 | 0.4 | 0.7 | 2.2% | 3.7% |
| 25 | Asphalt | 17.8 | 17.6 | 17.9 | 17.6 | 18.0 | 0.4 | 0.7 | 2.4% | 4.0% |
| 15 | Asphalt | 16.3 | 16.1 | 16.5 | 16.2 | 16.4 | 0.4 | 0.7 | 2.7% | 4.4% |
| 0 | Asphalt | 15.3 | 15.1 | 15.5 | 15.1 | 15.5 | 0.4 | 0.7 | 2.8% | 4.6% |
| -15 | Asphalt | 14.4 | 14.2 | 14.6 | 14.2 | 14.6 | 0.4 | 0.7 | 3.0% | 5.0% |
| 35 | Composite | 19 | 18.8 | 19.3 | 18.8 | 19.2 | -0.1 | 0.4 | -0.4% | 1.9% |
| 25 | Composite | 17.6 | 17.3 | 17.8 | 17.4 | 17.8 | -0.1 | 0.4 | -0.4% | 2.1% |
| 15 | Composite | 16.1 | 15.9 | 16.3 | 16.0 | 16.2 | -0.1 | 0.4 | -0.5% | 2.3% |
| 0 | Composite | 15.1 | 14.9 | 15.4 | 14.9 | 15.3 | -0.1 | 0.4 | -0.5% | 2.4% |
| -15 | Composite | 14.2 | 13.9 | 14.4 | 14.0 | 14.4 | -0.1 | 0.4 | -0.5% | 2.6% |
| 35 | Concrete | 18.7 | 18.6 | 18.9 | 18.5 | 18.9 |  |  |  |  |
| 25 | Concrete | 17.3 | 17.1 | 17.5 | 17.1 | 17.5 |  |  |  |  |
| 15 | Concrete | 15.8 | 15.8 | 16.0 | 15.7 | 15.9 |  |  |  |  |
| 0 | Concrete | 14.9 | 14.7 | 15.0 | 14.7 | 15.1 |  |  |  |  |
| -15 | Concrete | 13.9 | 13.7 | 14.1 | 13.7 | 14.1 |  |  |  |  |

Shaded cells indicate fuel consumption differences that are not statistically significant

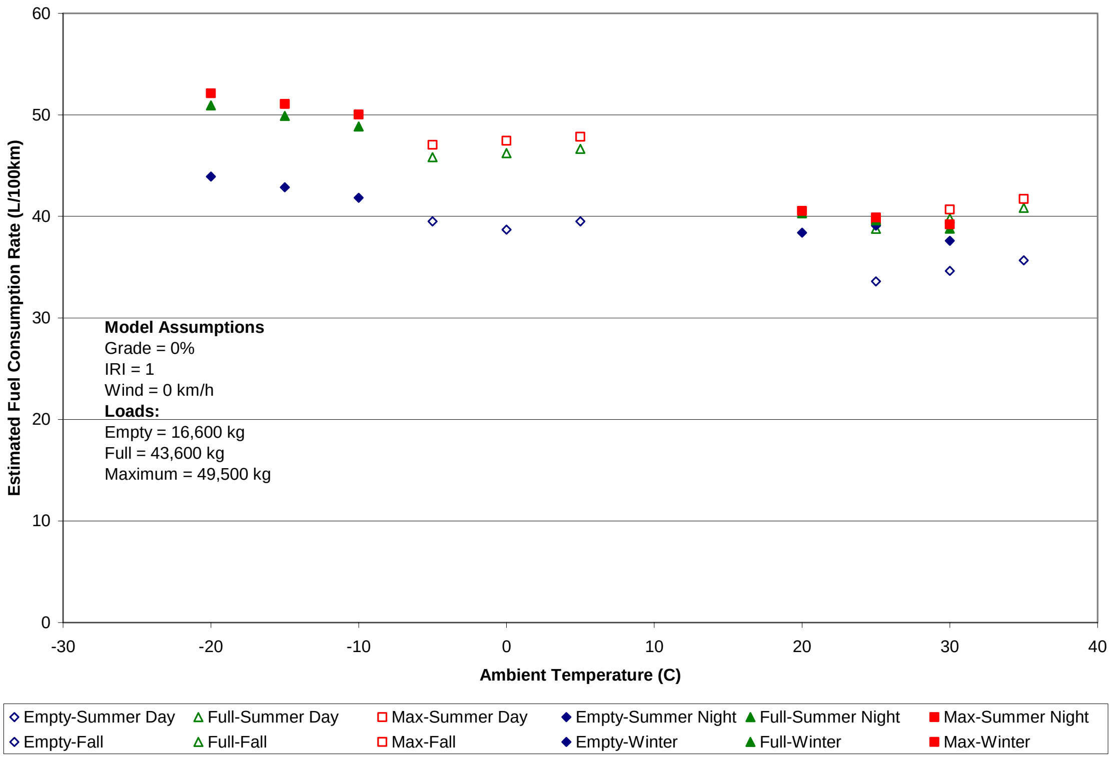

Figure 4-2 Truck Model Estimates – Concrete

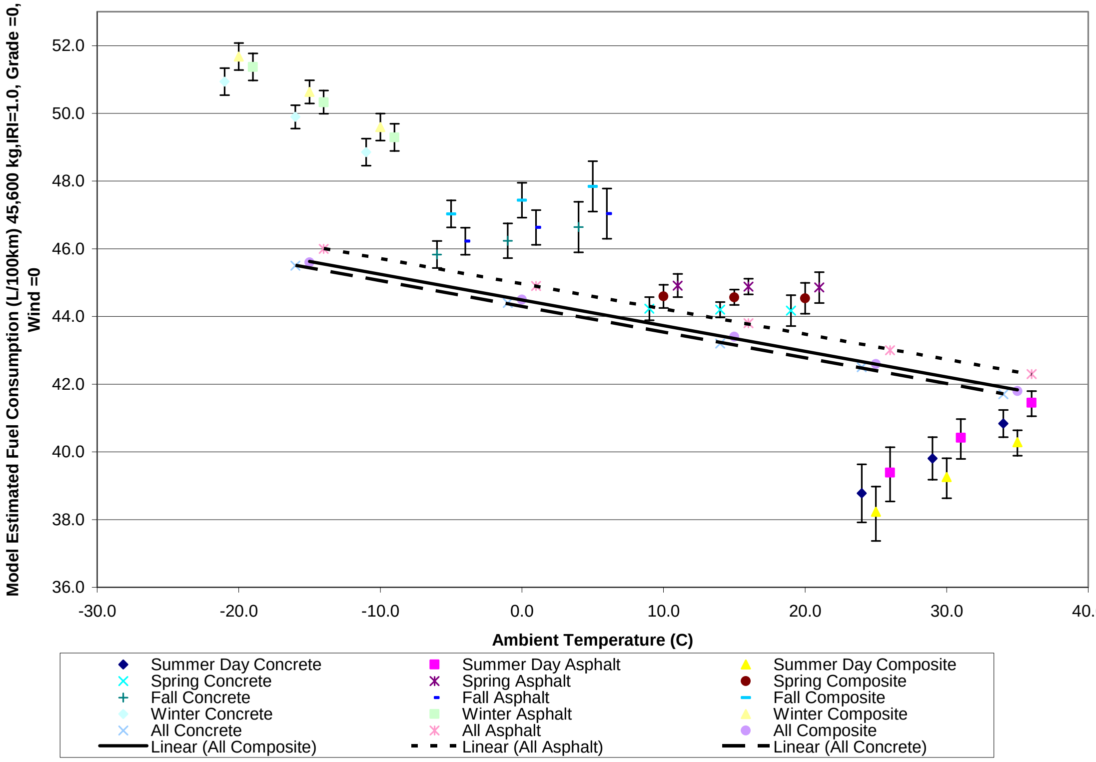

Figure 4-3 Truck Model Estimates, Full Load At 100 km/h (43,660 kg)

The results of the percentage change analysis for all load conditions at 100 km/h are presented in Figure 4-4 for the comparison of asphalt to concrete pavements and in Figure 4-5 for the composite to concrete comparison. Both these figures do not show the confidence bounds to allow clarity of presentation. However, examples of these bounds are presented for the full load condition for the asphalt to concrete comparison in Figure 4-7 and for the composite to concrete comparison in Figure 4-9. The corresponding comparisons at empty loading are found at Figures 4-6 and 4-8. Similar plots of the percentage changes at 60 km/h are provided at Figures 4-10 through 4-15.

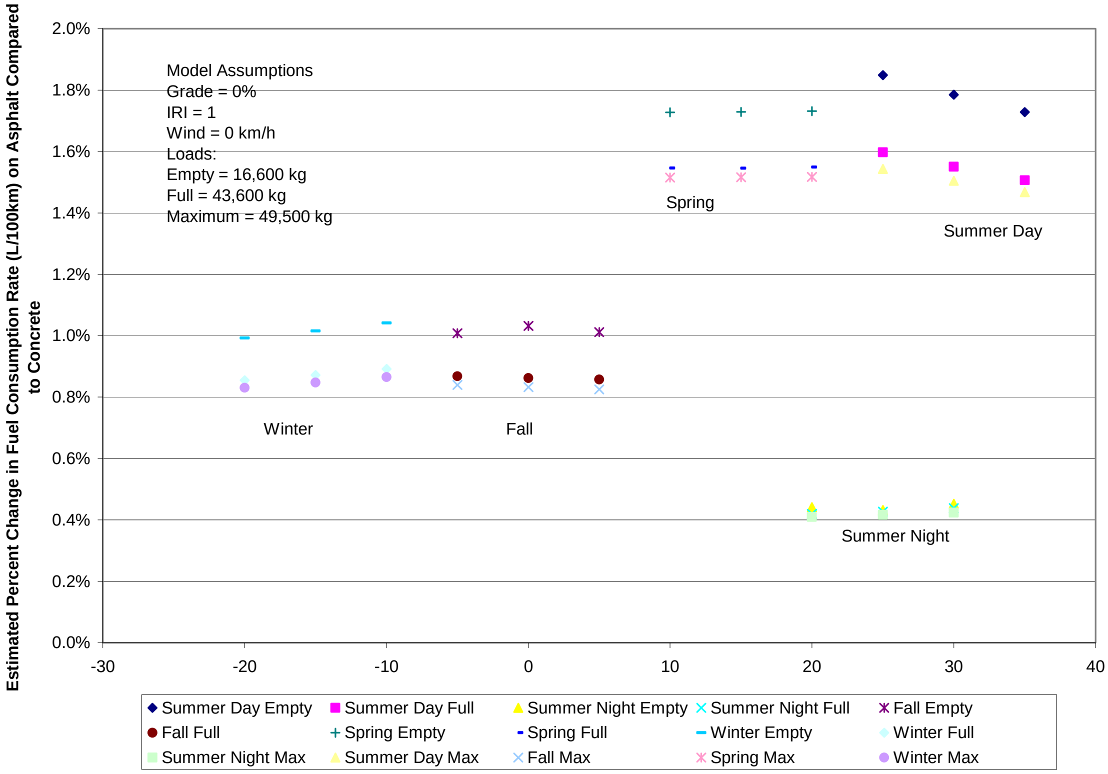

**Figure 4-4 Asphalt-Concrete Percentage Change Estimates at 100 km/h**

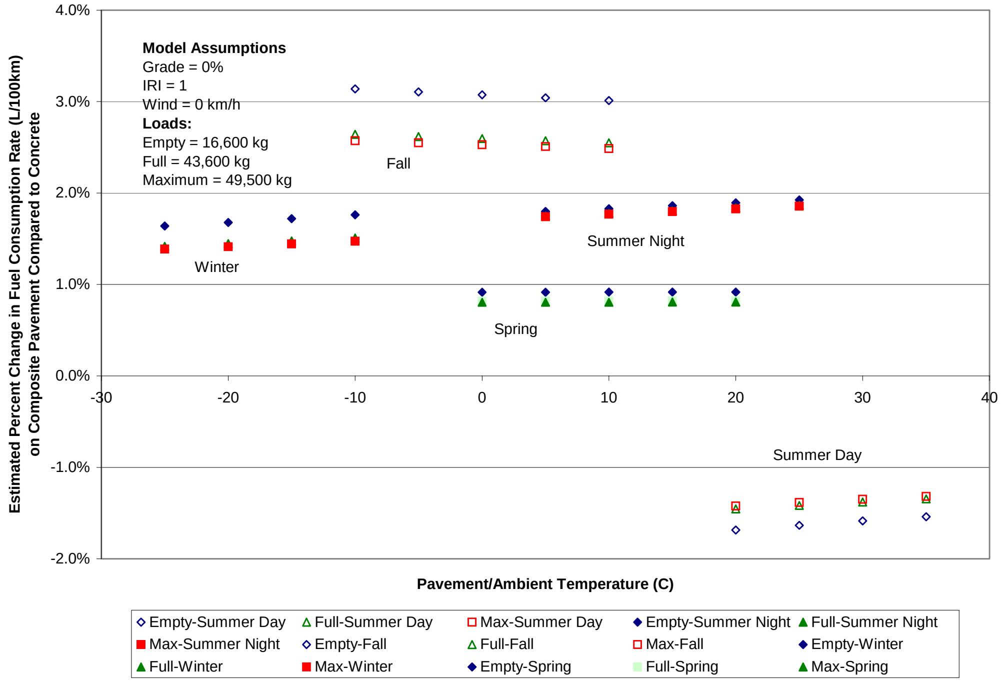

Figure 4-5 Composite-Concrete Percentage Change Estimates at 100 km/h

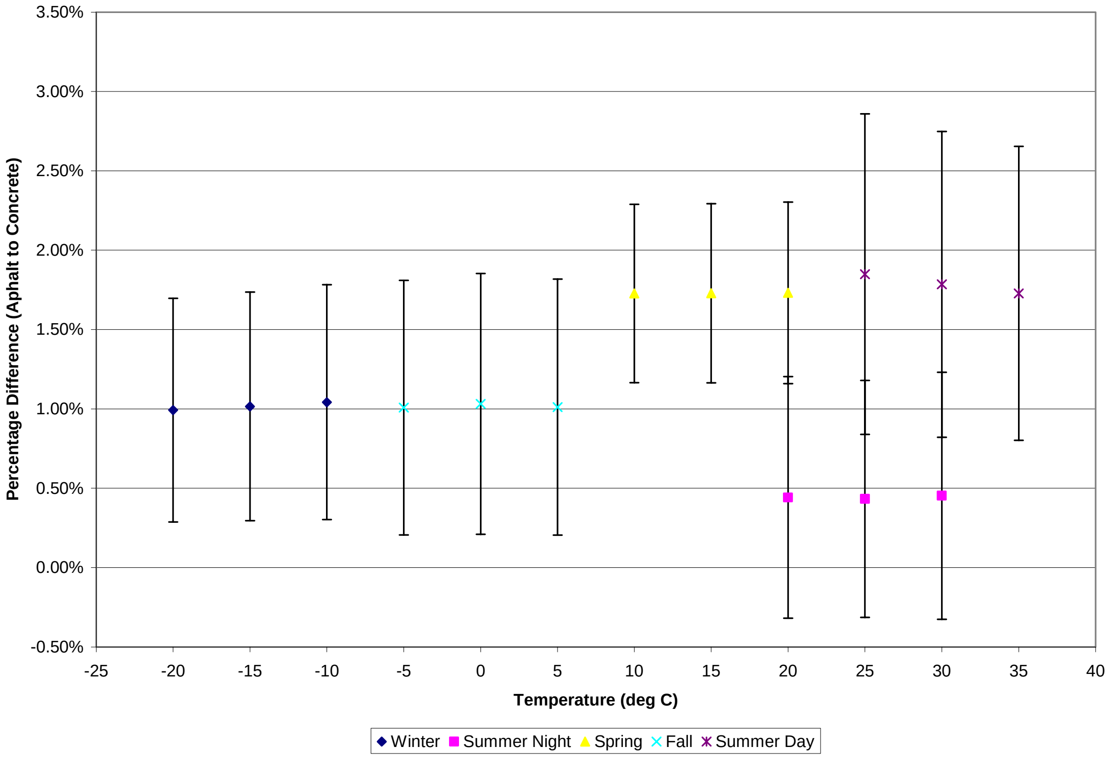

Figure 4-6 Asphalt 95% Confidence Bounds - Empty, 100 km/h

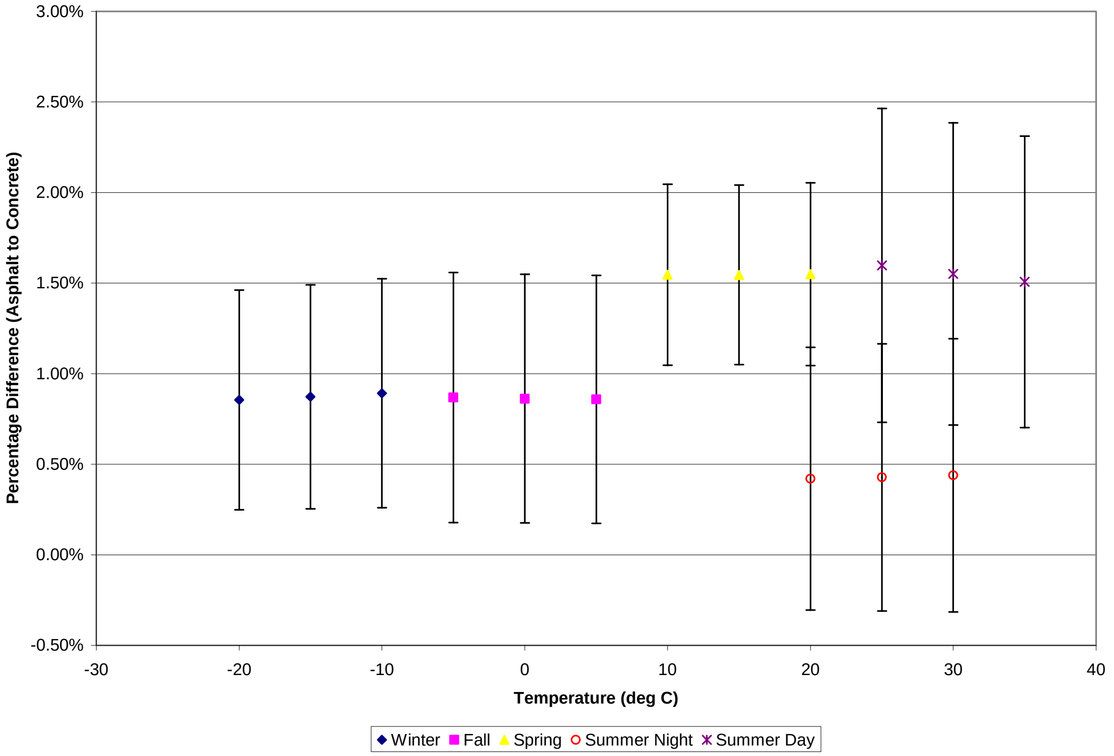

Figure 4-7 Asphalt 95% Confidence Bounds – Full Load at 100 km/h

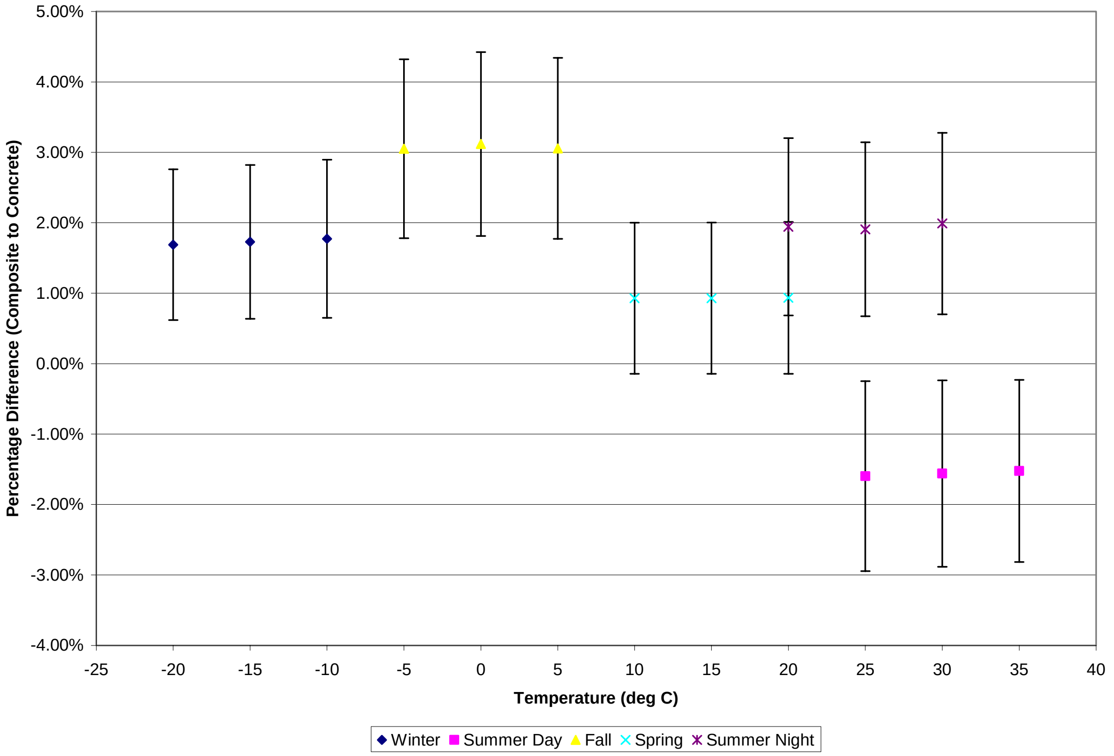

Figure 4-8 Composite, 95% Confidence Bounds - Empty, 100 km/h

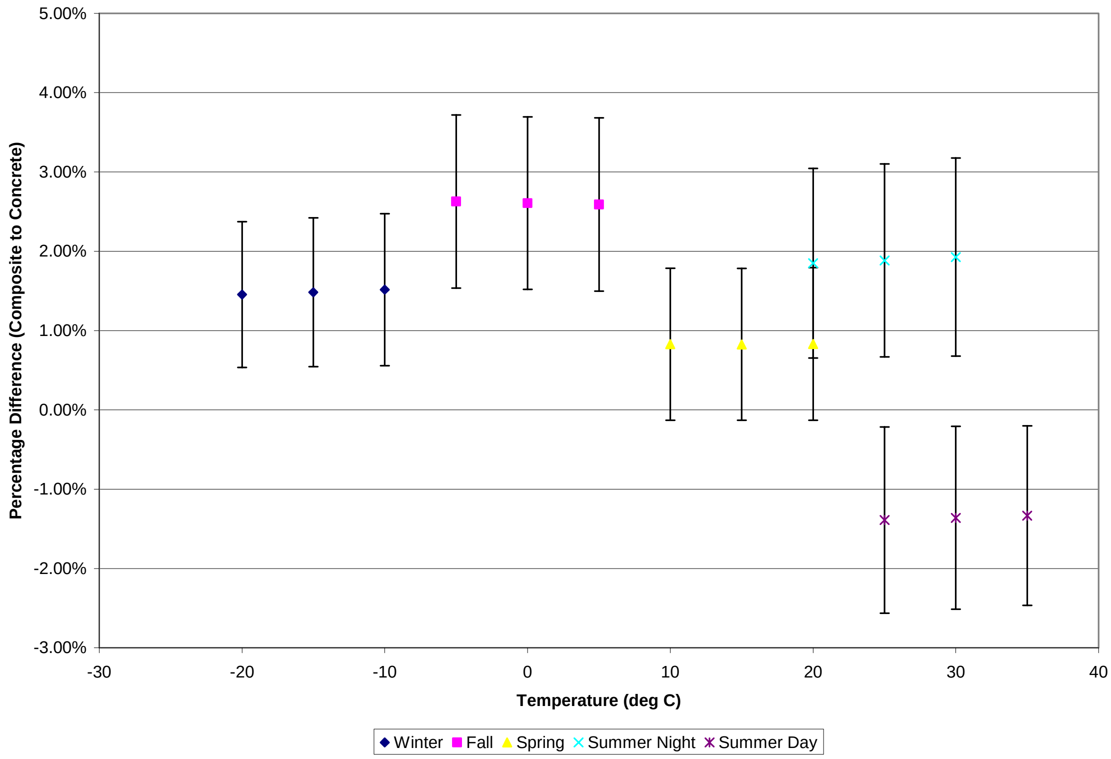

Figure 4-9 Composite, 95% Confidence Bounds, Full, 100 km/h

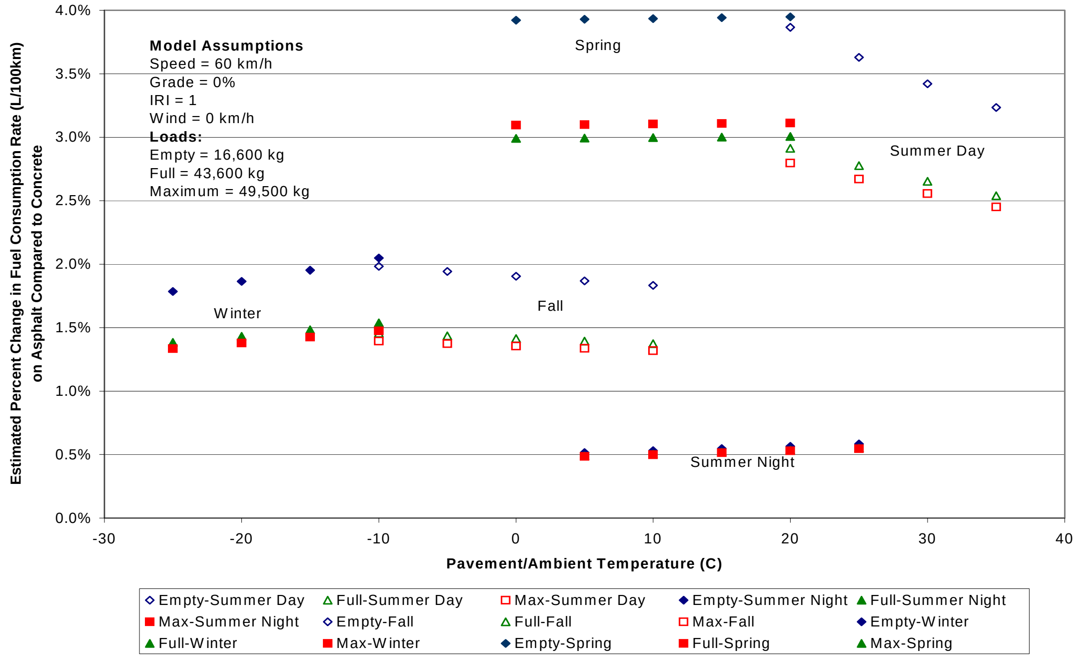

Figure 4-10 Asphalt Percent Change At 60 km/h (All loads)

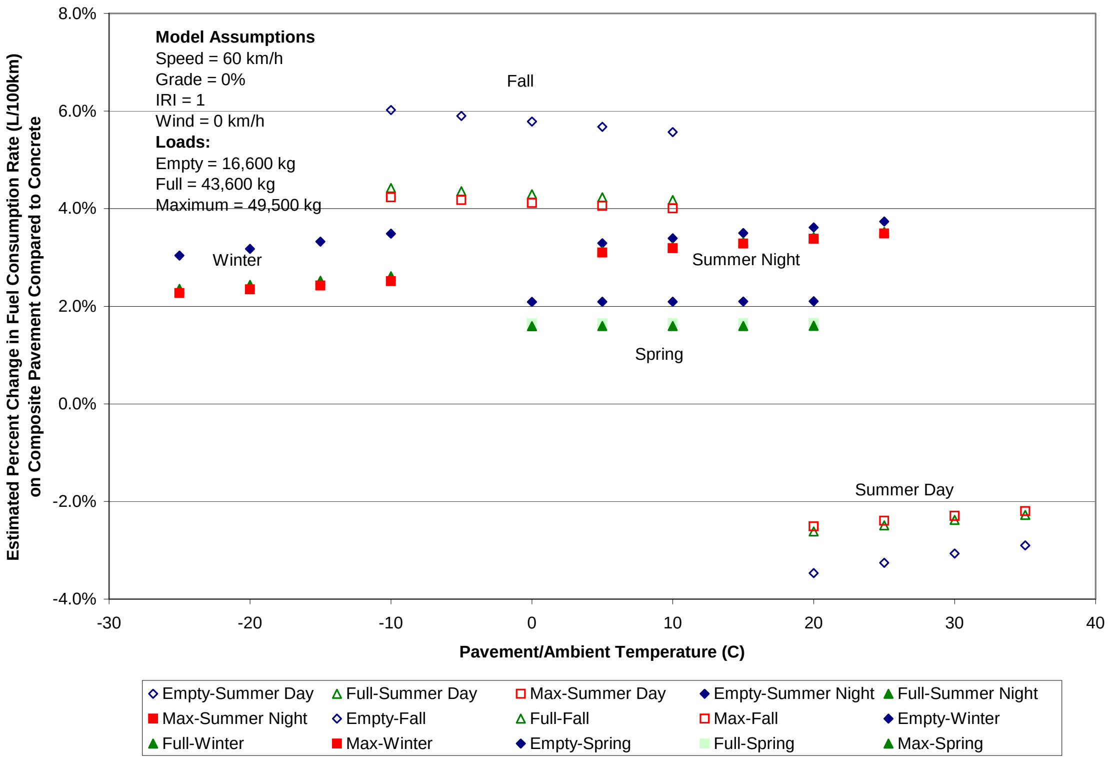

Figure 4-11 Composite Percent Change At 60 km/h (All loads)

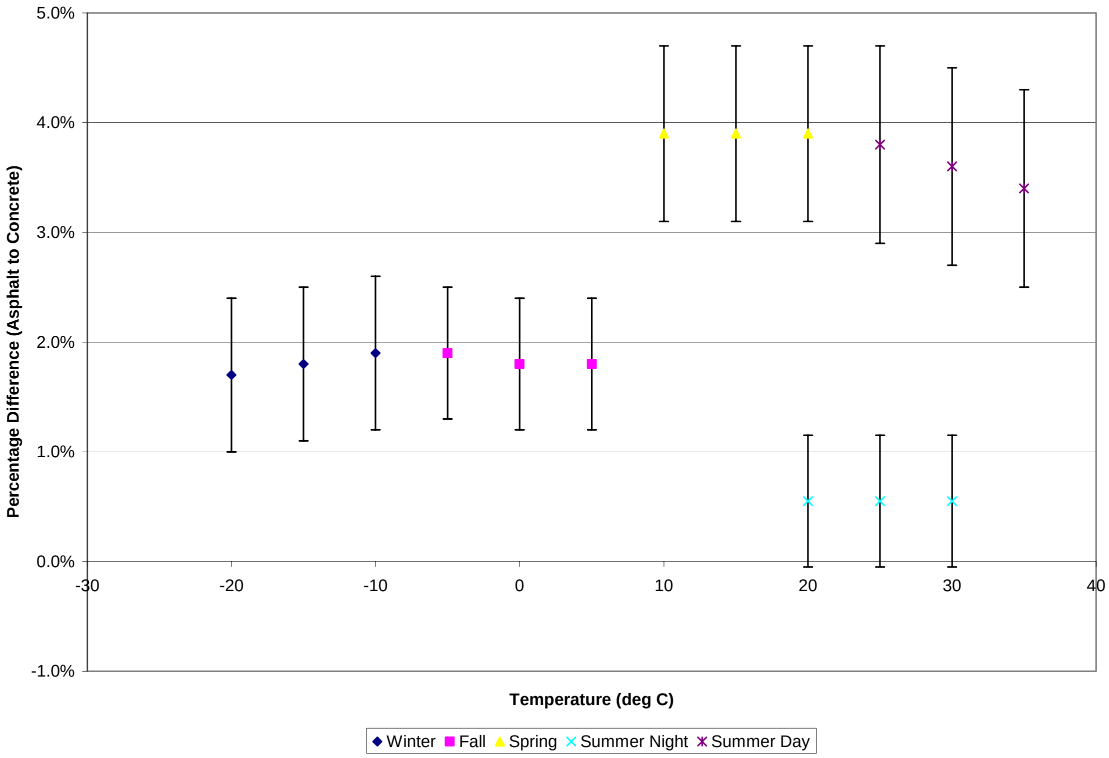

Figure 4-12 Asphalt Percent Difference- 95% Confidence Bounds, empty, 60 km/h

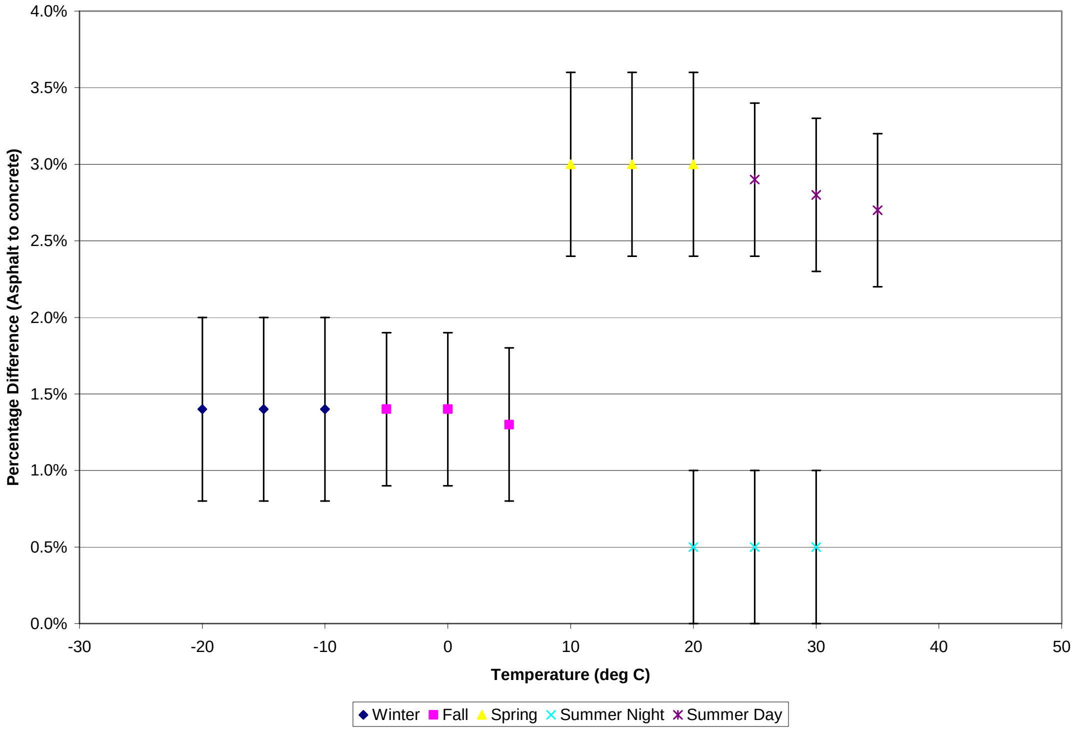

Figure 4-13 Asphalt, Percent Difference- 95% Confidence Bounds, full, 60 km/h

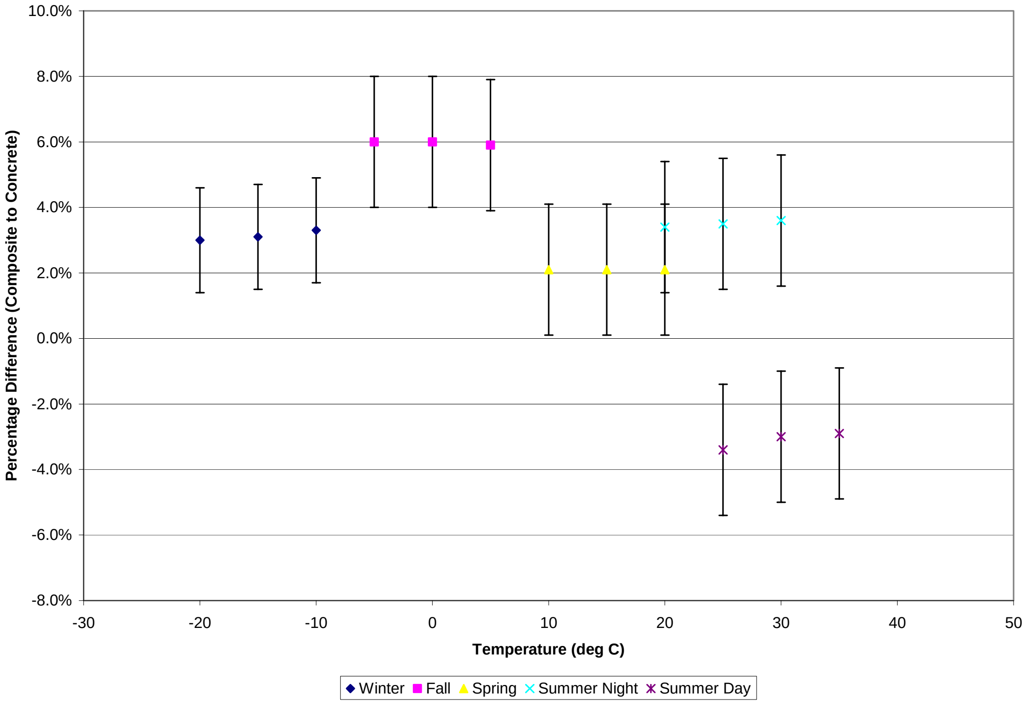

Figure 4-14 Comp. Percent Difference- 95% Confidence Bounds, empty, 60 km/h

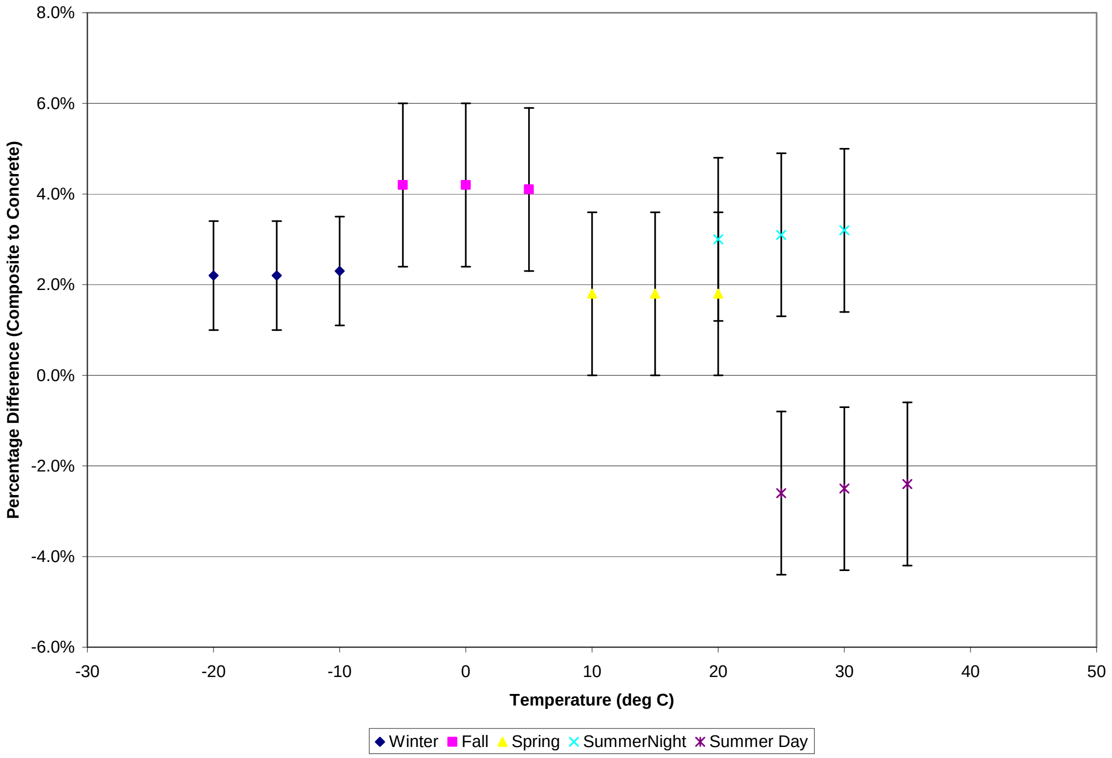

Figure 4-15 Comp. Percent Difference- 95% Confidence Bounds, full, 60 km/h

## 4.6 Phase III Truck Model Findings

There are a number of overall observations to be made from the truck point estimates:

- The Fall and Summer Day models have positive coefficients for pavement temperature and thus the fuel consumption increases with higher temperatures. This anomaly may have some basis in physics due to the plastic nature of the materials which may increase the rolling resistance at higher material temperatures;

- The Summer Night data is an anomaly as it indicates a very low sensitivity to load changes.

The fuel consumption difference analysis indicates that, if the 95% confidence bounds are considered:

- In all five seasons, the vehicle's fuel consumption increased when pulling the empty trailer while driven at 100 km/h over asphalt roads, compared to concrete roads. These differences ranged between 0.4 L/100 km to 0.7 L/100km (1.0% to 1.8%). All of these values were calculated to be statistically significant. There was a 0.2 L/100 km (0.4%) increase in fuel consumption on asphalt when compared to concrete in Summer Night data, however, these data were not statistically significant (Figure 4-6).

- In all five seasons, the vehicle's fuel consumption increased when pulling the full trailer while driven at 100 km/h over asphalt roads, compared to concrete roads. Theses differences ranged between 0.4 L/100 km to 0.7 L/100 km (0.8% to 1.6%). There was a 0.1 L/100 km (0.4%) increase in fuel consumption on asphalt when compared to concrete in Summer Night data, however, these data were not statistically significant (Figure 4-7).

- In four of the five seasons, the vehicle's fuel consumption increased when pulling the empty trailer while driven at 100 km/h over composite roads, compared to concrete roads. This increase ranged between 0.2 L/100km to 1.5 L/100km (1.0% to 3.1%). However, the difference for summer day data was roughly -0.5 L/100km (-1.5%), indicating a decrease in fuel consumption on composite roads, when compared to concrete. All these differences were found to be statistically significant with the exception of the Spring data which was not significant (Figure 4-8).

- In four of the five seasons, the vehicle's fuel consumption increased when pulling the full trailer while driven at 100 km/h over composite roads, compared to concrete roads. This increase ranged between 0.4 L/100 km to 1.2 L/100 km (0.8% to 2.6%). However, the difference for summer day data was roughly -0.5 L/100 km (-1.3%), indicating a decrease in fuel consumption on composite when compared to concrete. All these differences were found to be statistically significant with the exception of the Spring data which was not significant (Figure 4-9).

- The multi regression analysis models (winter, spring, summer day/night, fall and all-season) all have positive asphalt pavement coefficient values, indicating lower fuel consumption on concrete pavement compared to asphalt pavement. In addition, all but one composite pavement coefficient values are positive.

- 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. Figure 4-12.

- The fuel savings for the full trailer at 60 km/h when comparing concrete to asphalt roads ranged from 0.2 L/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. Figure 4-13.

- 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. Figure 4-14.

- 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. Figure 4-15.

# 5 COAST DOWN TESTS

## 5.1 Coastdown Procedure

The use of vehicle coastdown tests allows for the direct observation and measurement of the drag forces on a rolling vehicle. The basic method is defined by the Society of Automotive Engineers (SAE) test method standard SAE J2263 -- Road Load Measurement Using On-Board Anemometry and Coastdown.

The SAE test methods are aimed at measuring all the road forces that affect a vehicle, including aerodynamic and rolling drag using a “batch” test file – i.e. the starting speed and end speed and starting time and end time and collect one data set per coastdown test. The tests are required to be repeated at least 10 tmes in both directions to allow for a large enough data set for statistical analysis and to compensate for any relative wind influences. Also, the test method involve a high-speed coastdown portion as well as a low-speed coastdown. The test method requires a starting speed of 125 km/h (for the aero drag coefficient) and the lowest end speed to be below 15 km/h (for the rolling drag coefficient).

As this research program was only interested in assessing the change in rolling drag and CSTT had access to both realtime engine/vehicle information, wind speed and the exact grade and curvature of the roadway, the study team developed a modified test protocol aimed at measuring only a low-speed coastdown and extracting drag-coefficient-related data from the collected data. The principal advantage in performing low-speed coastdowns was that it required less lineal length of roadway and thus it was operationally much easier, safer and faster. Further, with the availablity of continuous data (2-3 Hz.) a large number of data points during one coastdown trial were available – unlike the standard SAE method that produces one data point per coastdown. Also, because the road grade and curvature as well as instantaneous wind speeds were avaialble, these could be treated as independent variables in a multiple regression analysis. Finally, while bi-directional tests were conducted on two of the sites (1 e/w and 5 e/w) these tests were in fact on opposing sections of roadway (the alternate lane) and thus the road grades and underlying road structures were not necessarily the same. Thus, each test site was analyzed separately.

The coastdown tests required the following steps:

1. The vehicle was loaded to the test condition (49,400 kg GVW) and all tires checked for condition and pressure.
2. The vehicle was driven at least one hour to fully warmup the drivetrain, tires and wheel bearings.
3. The vehicle speed was reduced to approximately 30 km/h at the start of the test section and the clutch disengaged (all windows were closed and brake fully disengaged). The vehicle and wind data logging was started.
4. The vehicle was then allowed to freely decelerate to approximately 10 km/h or until the end of the test section was reached.
5. Coastdowns were repeated a minimum of three times and in both directions, where possible. Bi-directional testing was conducted on opposing East and West bound lanes as it was impossible to close roads and perform bi-directional testing on one side of the highway.

6. The average ambient wind conditions were required to be less than 10 km/h, and no precipitation was allowed.
7. A minimum of two complete tests were completed on each test section.

Because of the extremely slow speed that the vehicle travels on the high-speed highway (where the speed limit was 100 km/h), significant safety measures had to be employed during the testing. This involved the notification of the local provincial police and the hiring of two safety trucks which were equipped with collision bumpers and large flashing directional signs which travelled behind the test truck by some 200 to 300m. This procedure appeared to be effective in moving traffic around the test convoy although there were instances of vehicles moving into the passing lane as they approached the warning trucks and moving back into the right hand lane between the warning trucks and the test vehicle.

## 5.2 Test Sites

A total of six test sections of roadway were used for the coastdown testing. They represented three asphalt sections (Site 1 - Highway 417 East and West near Carp, site 11 -- Highway 417 near Casselman), one concrete (Site 2 - Highway 417 East of Casselman) and two composite sections (Site 5 - Highway 401 East and West near Prescott). For each pavement test section, a detailed analysis of the road gradient through the section was undertaken prior to the tests and specific portions selected which exhibited the most level conditions possible. The longitudinal elevations of the sections are graphically portrayed in the following figures.

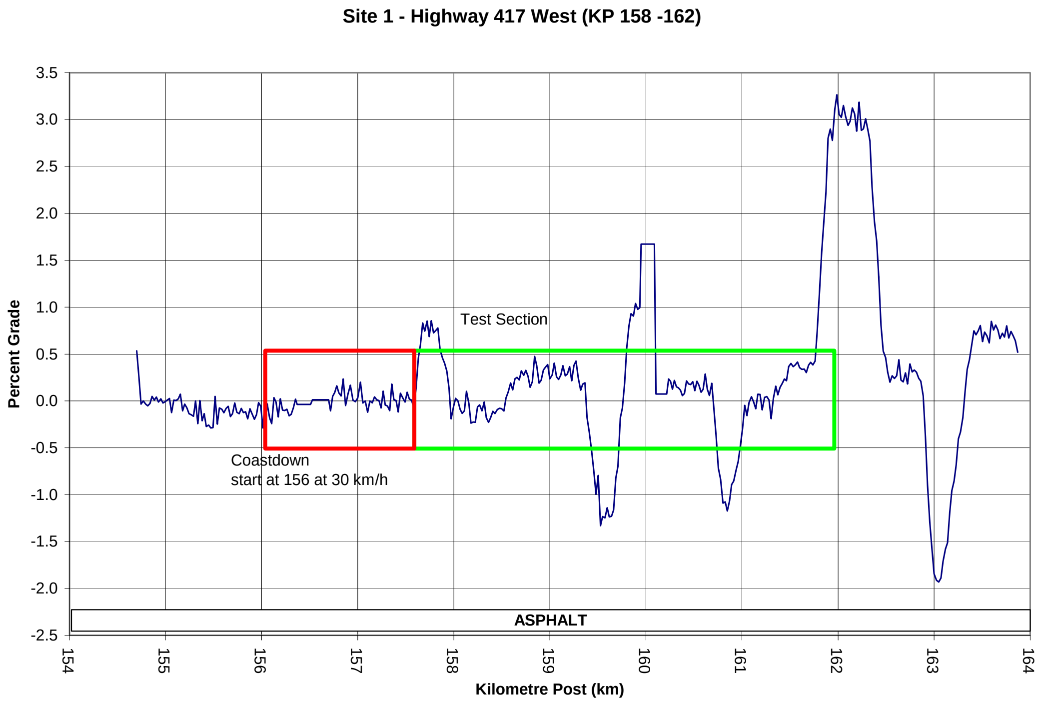

Figure 5-1 Site 1 West Coastdown Test Area

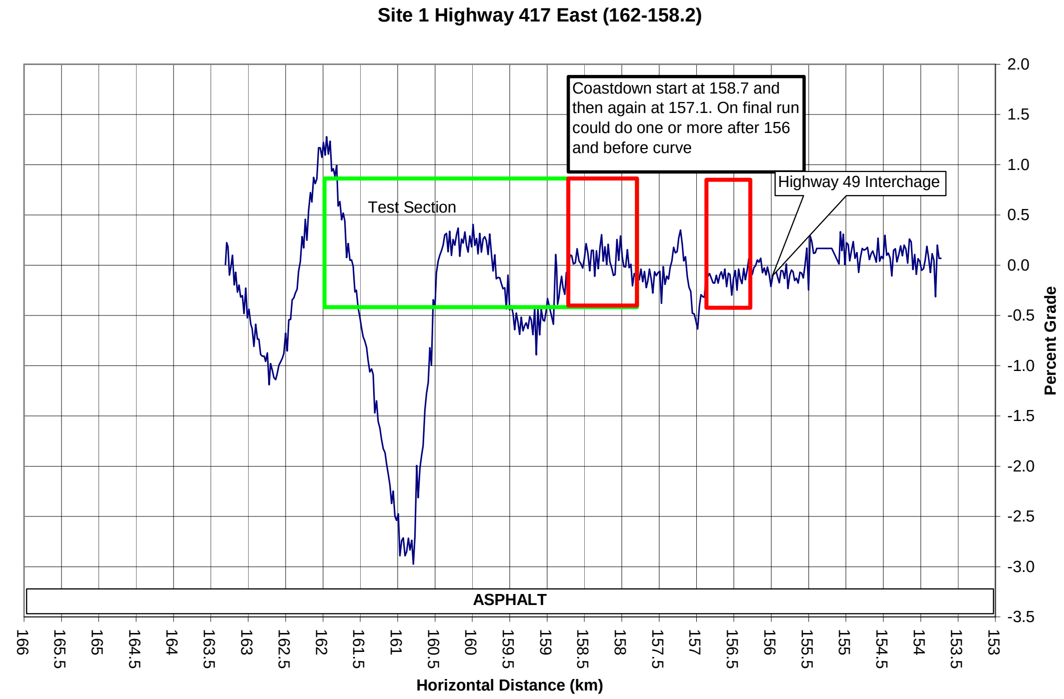

Figure 5-2 Site 1 East Test Areas

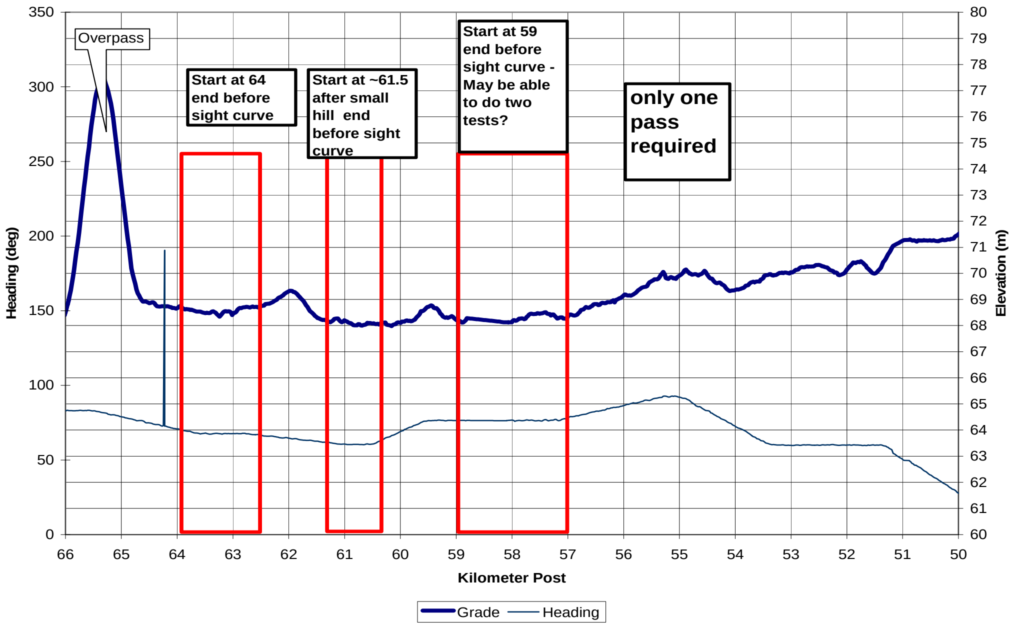

Figure 5-3 Site 11 East Coastdown Test Sites

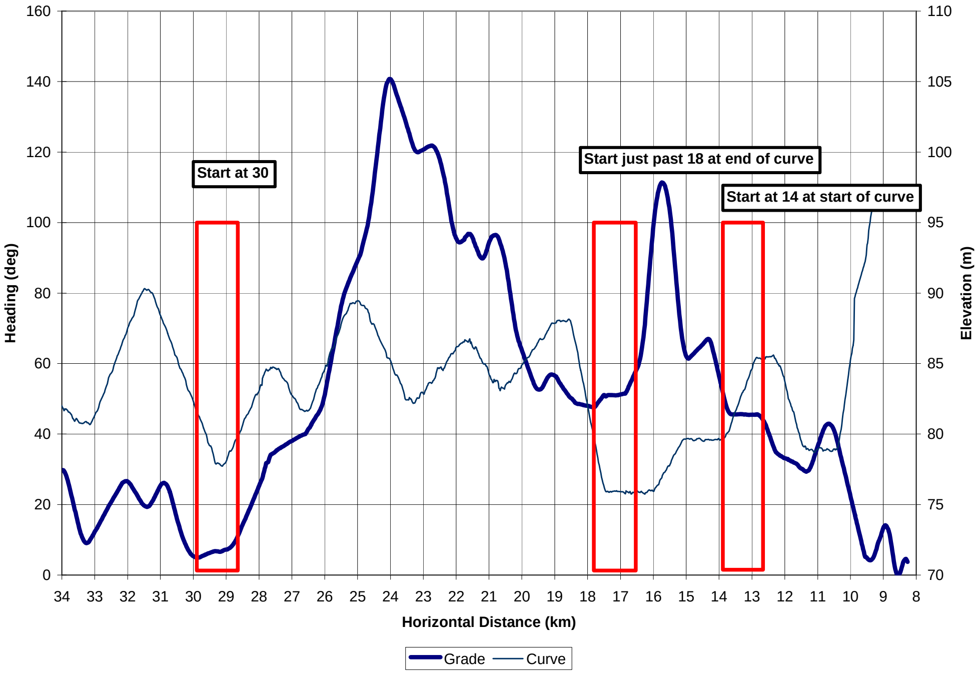

Figure 5-4 Site 2 East Coastdown Test Areas

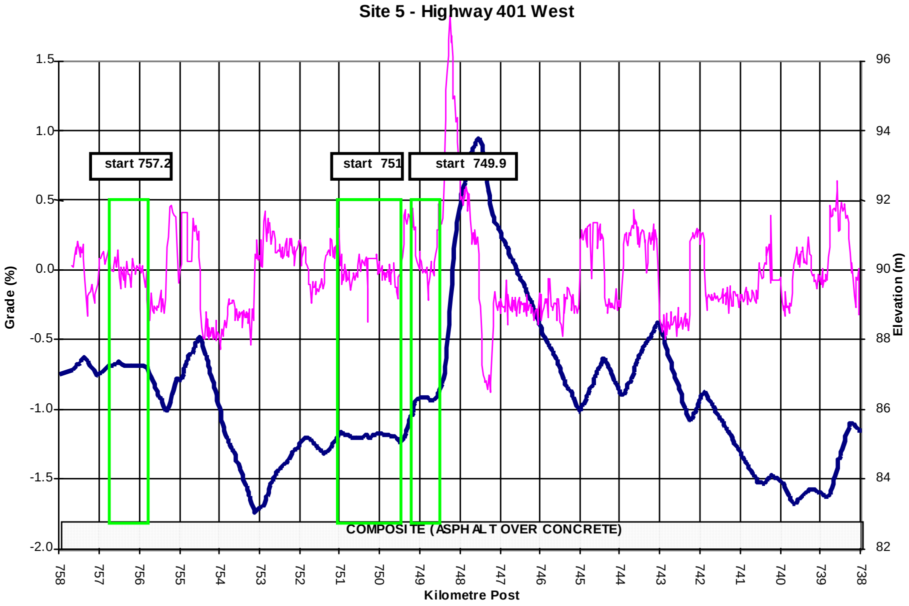

Figure 5-5 Site 5 West Coastdown Test Areas

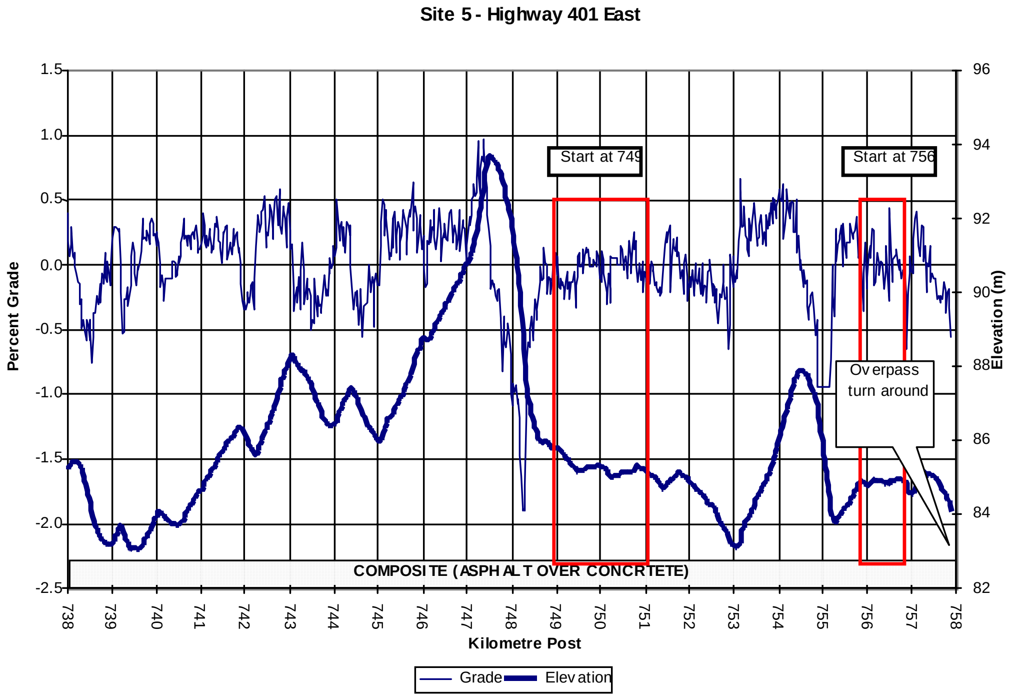

**Figure 5-6 Site 5 East Coastdown Test Areas**

## 5.3 Test Results

The coastdown tests were completed in late August 2003. The testing was undertaken in the evening so that traffic conditions and winds were the lightest possible. Test conditions are presented in Table 5-1 and an example set of test data is plotted (speed vs. time) in Figure 5-7. It can be noted in Figure 5-7, a simple plot of vehicle speed against time, that the deceleration rate (the slope is the regression equation first coefficient) exhibited relatively good repeatability on the six coastdown tests (2 sub-sections per pass and 3 passes). All test sections had high measures of repeatability. A total of 1299 data points were collected on the 6 sites.

The continuous data were analysed in a multiple regression model which included variables for the time, instantaneous wind speed, instantaneous grade and instantaneous curvature. The analysis indicated (Table 5-2) that the most significant explanatory factor was simply the time (deceleration rate). The other factors were all significant explanatory variables on some of the sites (all the variables were statistically significant on at least one of the sites) but all the additional variables together only improved the over coefficient of determination ($R^2$) by 2-3% with 88 to 94% of the variation being explained by the time variable.

**Table 5-1 Coastdown Test Conditions**

| Test Conditions | Site 1E Asphalt | Site 1W Asphalt | Site 11E Asphalt | Site 2E Concrete | Site 5E Composite | Site 5W Composite |
|---|---|---|---|---|---|---|
| Date | 28/8/03 | 28/8/03 | 28/8/03 | 28/8/03 | 28/8/03 | 28/8/03 |
| Ambient Temperature (C ) | 17.8 | 17.8 | 11.20 | 11 | 12.4 | 12.4 |
| Pavement Temperature (C ) | 20 | 20 | 14 | 12.8 | 13.8 | 13.8 |
| Average Ambient Wind (km/h) | -4.5 | +2.7 | -0.6 | -1.4 | -0.5 | +0.4 |

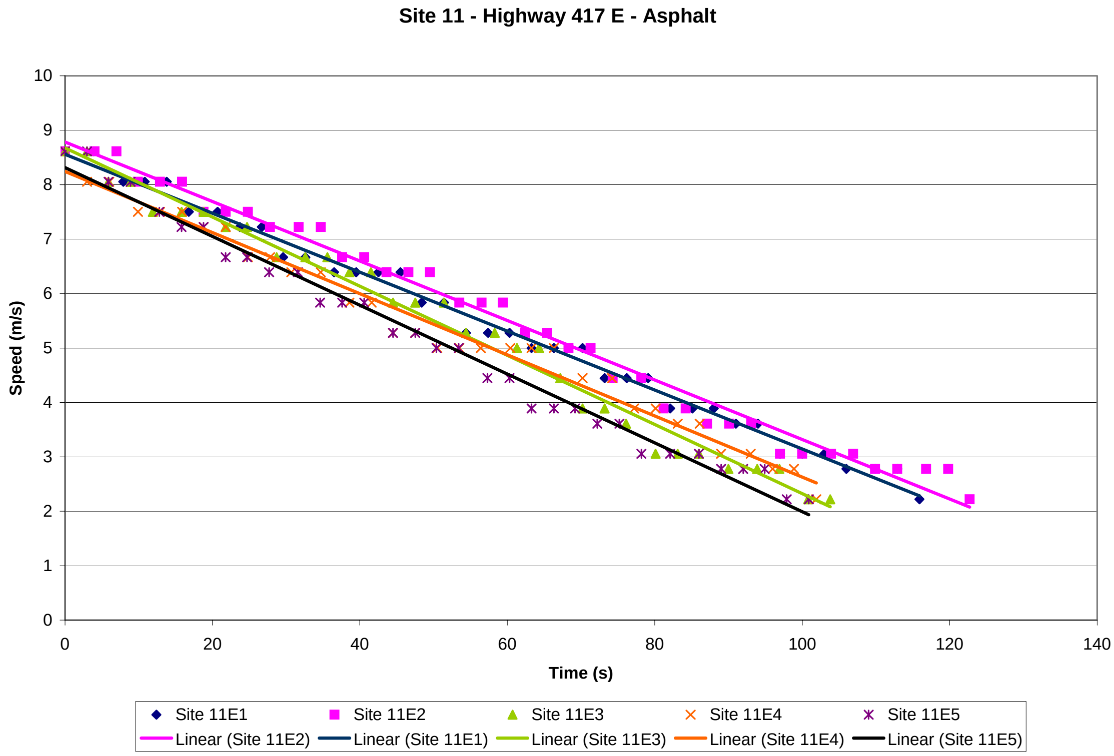

Figure 5-7 Coastdown Speed vs. Time at Site 11 East - Asphalt

Looking just at the acceleration measure (time), which is the measure of the rolling force differences between the pavements, there is not consistent difference between the concrete and other pavements (see Table 5-2 and Figure 5-8). Between the concrete and composite pavements there are no consistent differences with one composite coefficient higher (-0.055) and the other lower (-0.051) than the concrete coefficient (-0.054). The three asphalt sections exhibit substantially wider spreads in their coefficients (-0.046 to –0.64) again straddling the concrete value. The higher variation in the 1E/W test site may in part be due to the differences in the pavement structure (the East lane was part of the original highway while the West lane was new construction when built).

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## Table 5-2 Regression Equation Summary

| Statistical Coefficients | Test Site and Pavement Type | | | | | |
|---|---|---|---|---|---|---|
| | 1E 417 Asphalt | 1W 417 Asphalt | 11E 417 Asphalt | 2E 417 Concrete | 5E 401 Composite | 5W 401 Composite |
| Number of Runs | 3 | 3 | 3 | 2 | 2 | 2 |
| Intercept | 7.71 | 8.82 | 8.42 | 8.70 | 8.82 | 8.67 |
| Time (s) | -0.046 | -0.064 | -0.056 | -0.054 | -0.051 | -0.055 |
| Wind Speed (km/h) | -0.074 | 0.003 | -0.052 | -0.016 | -0.018 | 0.000 |
| % Grade | -0.119 | 1.762 | 0.403 | 0.426 | -0.282 | 0.275 |
| % Curve | 0.089 | 0.045 | -0.099 | 0.559 | 0.035 | 0.006 |
| Speed=a+b*Time+c*Wind+d*%Grade+e*%curve | | | | | | |
| Observations | 304 | 148 | 176 | 219 | 232 | 220 |
| $R^2$ | 0.897 | 0.960 | 0.973 | 0.922 | 0.938 | 0.950 |
| Standard Error | 0.597 | 0.376 | 0.317 | 0.552 | 0.479 | 0.422 |
| Adjusted $R^2$ | 0.895 | 0.959 | 0.972 | 0.921 | 0.937 | 0.949 |
| Multiple R | 0.947 | 0.980 | 0.986 | 0.960 | 0.969 | 0.975 |

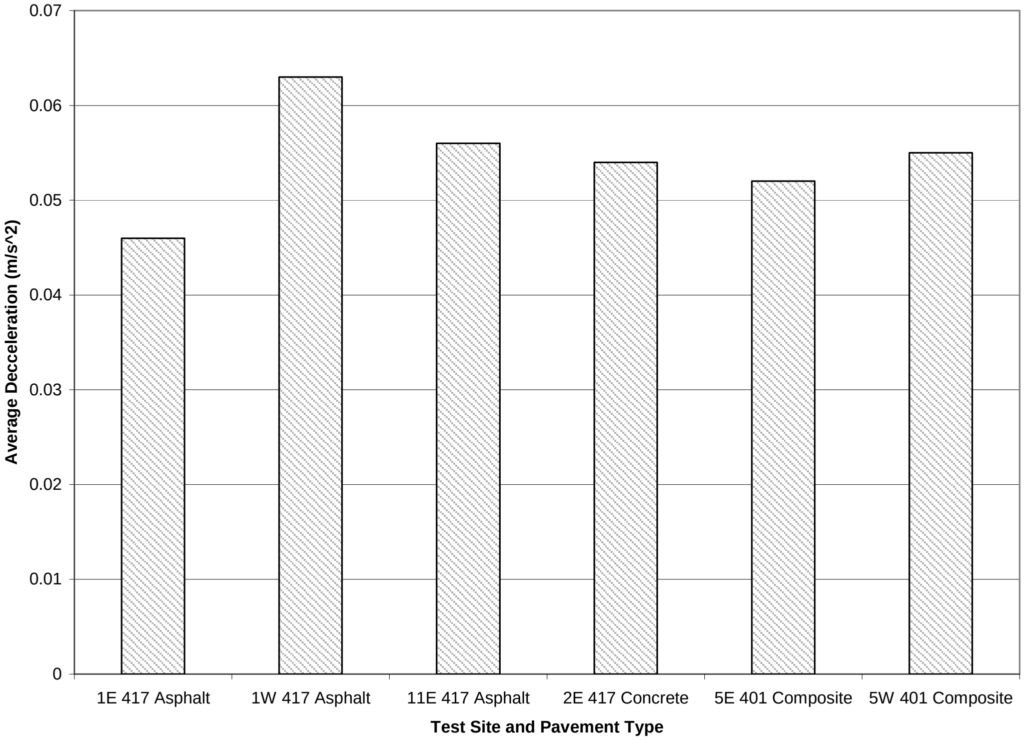

Figure 5-8 Coastdown Average Decceleration Rates

## 5.4 Coastdown Findings

The following findings are made based on the tractor trailer coastdown test data:

- The coastdown tests were successfully completed and met all the test conditions required.

- Excellent repeatability of the tests was achieved.

- The test results were analysed by means of a multiple regression model which allowed for the estimation of each independent variable's (rolling resistance (time), wind speed, grade, and curvature) coefficient to be measured. Comparing the rolling resistance (time) coefficient of concrete to the other pavements does not indicate any consistent differences between pavement types.

# 6 PASSENGER CAR TESTS

## 6.1 Test Method

Measurement of the impact of pavement differences on a passenger car's fuel consumption were undertaken following similar test criteria and procedures as those used in the truck test program. The vehicle was equipped with a communication cable connected to the onboard diagnostic (OBDII) engine communication system on the vehicle with laptop computer recording the information. The test sites were the same as those used in the truck program and the test conditions included winter and summer temperature ranges. Note that the sample rate for these data was approximately three times that available for the truck testing.

The winter car tests were performed after the winter truck test program had been completed in early March 2003. The pavement temperature conditions ranged from -11 to +5°C. The summer tests were undertaken after the summer truck test program was completed in September 2003. The pavement temperature conditions for the summer tests ranged from +20 to +34 °C. All the other test condition criteria were met during the tests.

The data were processed in a similar manner to the truck data with the raw data being merged into meta-files and then these files being processed using the Minitab statistical analysis program. The model form used was the same as that used in the truck model with the exception that there was no variation in load in the test data. As with the truck analysis, the results were based on the model, which included an IRI ranging from 0 to 2.

## 6.2 Data Analysis

### 6.2.1 Car Winter Model

The data set for the winter testing contained 28,517 observations. The regression modeling resulted in the following regression equation:

$$\text{FuelCon} = 12.6 + 0.285\ \text{Pvash} - 0.227\ \text{Pvcomp} - 0.0417\ \text{IRI} + 2.03\ \text{Grade} - 0.0607\ \text{Pavetemp} - 0.0509\ \text{Speed} + 0.000202\ \text{AirSpdSq}$$

As shown in the following table, all the variables were measured as being significant to explaining the said data. However, overall the coefficient of determination (R- Sq) is only 47.9%, which is acceptable but significantly lower than that obtained for the truck testing data.

**Table 6-1 Car Winter Model Coefficients**

| Predictor | Coef | SE Coef | t-test | P-test |
|---|---|---|---|---|
| Constant | 12.6184 | 0.0535 | 235.94 | 0 |
| Pvash | 0.28465 | 0.0139 | 20.48 | 0 |
| Pvcomp | -0.22678 | 0.02035 | -11.14 | 0 |
| IRI | -0.04169 | 0.02029 | -2.06 | 0.04 |
| Grade | 2.02976 | 0.01453 | 139.74 | 0 |
| Pavetemp | -0.06071 | 0.003584 | -16.94 | 0 |
| Speed | -0.05092 | 0.00087 | -58.51 | 0 |
| AirSpdSq | 0.000202 | 5.06E-06 | 39.86 | 0 |
| Number of Observations 28,517 $R^2$ = 47.9% | | | | |

### 6.2.2 Car Summer

The car Summer testing program collected essentially the same number of observations (28,913) as the winter data set. Again, the same model formulation was used as for the winter data and resulted in the following equational form:

FuelCon = 14.2 - 0.0263 Pvash + 0.125 Pvcomp - 0.0772 IRI + 1.78 Grade - 0.0462 Pavetemp - 0.0744 Speed +0.000252 AirSpdSq

Table 6-2 presents the statistical indicators for each variable and again the significance of all the variables is high. The overall explanatory power of the model is almost identical to the Winter model.

**Table 6-2 Summer Car Model Coefficients**

| Predictor | Coef | SE Coef | t-test | P-test |
|---|---|---|---|---|
| Constant | 14.2340 | 0.0720 | 197.69 | 0.000 |
| Pvash | -0.02632 | 0.01313 | -0.20 | 0.045 |
| Pvcomp | 0.12501 | 0.02097 | 5.96 | 0.000 |
| IRI | -0.07724 | 0.02056 | -3.76 | 0.000 |
| Grade | 1.77961 | 0.01477 | 120.49 | 0.000 |
| Pavetemp | -0.046154 | 0.002231 | -20.69 | 0.000 |
| Speed | -0.0743939 | 0.0007668 | -97.02 | 0.000 |
| AirSpdSq | 0.00025224 | 0.00000398 | 63.38 | 0.000 |
| Number of observations 28,913 $R^2$=48.3% | | | | |

## 6.3 Car Data Point Estimates

Each table below gives point estimates, as well as 95% and 99% confidence bounds for expected fuel consumption for cars on smooth road surfaces. Increases in expected fuel consumption for asphalt and composite surfaces relative to concrete are also given. All calculations are based on an IRI of 1.0, a vehicle speed of 100 km/hr, an air speed of 100 km/hr (assuming a wind speed of 0 km/hr), and a grade of 0.

For the winter point estimates, ambient temperatures of -10, -5, and 0 degrees Celsius are assumed. And for the summer model, temperatures of 20, 25, and 30 degrees Celsius are assumed. The resulting point estimates are provided along with their 95th percentile confidence bounds (once again calculated as a combined 97.5% confidence as explained in Section 4.5). Also the percentage change from concrete pavement for both the asphalt and composite pavements are calculated for each test condition plus their confidence bounds. The estimates are presented in Tables 6-3 and 6-4. The data is presented graphically in Figure 6-1 and Figure 6-2.

**Table 6-3 Car Winter Point Estimates, 100 km/h**

| Pave Temp | Surface | Estimate | 95 Lower | 95 Upper | 97.5 Lower | 97.5 Upper | Absolute Diff (low) L/100km | Absolute Diff (High) L/100km | Percent Diff (low) | Percent Diff (high) |
|---|---|---|---|---|---|---|---|---|---|---|
| 0 | Asphalt | 9.8 | 9.8 | 9.8 | 9.8 | 9.8 | 0.2 | 0.3 | 2.7% | 3.3% |
| -5 | Asphalt | 10.1 | 10.1 | 10.1 | 10.1 | 10.1 | 0.2 | 0.3 | 2.6% | 3.2% |
| -10 | Asphalt | 10.4 | 10.3 | 10.5 | 10.3 | 10.5 | 0.2 | 0.3 | 2.5% | 3.2% |
| 0 | Composite | 9.3 | 9.3 | 9.3 | 9.3 | 9.3 | -0.3 | -0.2 | -2.9% | -1.9% |
| -5 | Composite | 9.6 | 9.6 | 9.6 | 9.6 | 9.6 | -0.3 | -0.2 | -2.8% | -1.9% |
| -10 | Composite | 9.9 | 9.8 | 10.0 | 9.8 | 10.0 | -0.3 | -0.2 | -2.7% | -1.8% |
| 0 | Concrete | 9.5 | 9.5 | 9.5 | 9.5 | 9.5 |  |  |  |  |
| -5 | Concrete | 9.8 | 9.8 | 9.8 | 9.8 | 9.8 |  |  |  |  |
| -10 | Concrete | 10.1 | 10.0 | 10.2 | 10.0 | 10.2 |  |  |  |  |

**Table 6-4 Car Summer Point Estimates, 100 km/h**

| Pave Temp | Surface | Estimate | 95 Lower | 95 Upper | 97.5 Lower | 97.5 Upper | Absolute Diff (low) L/100km | Absolute Diff (High) L/100km | Percent Diff (low) | Percent Diff (high) |
|---|---|---|---|---|---|---|---|---|---|---|
| 30 | Asphalt | 7.8 | 7.7 | 7.9 | 7.7 | 7.9 | -0.1 | 0.0 | -0.7% | 0.0% |
| 25 | Asphalt | 8.1 | 8.1 | 8.1 | 8.1 | 8.1 | -0.1 | 0.0 | -0.7% | 0.0% |
| 20 | Asphalt | 8.3 | 8.2 | 8.4 | 8.2 | 8.4 | -0.1 | 0.0 | -0.7% | 0.0% |
| 30 | Composite | 8.0 | 7.9 | 8.1 | 7.9 | 8.1 | 0.1 | 0.2 | 1.0% | 2.2% |
| 25 | Composite | 8.2 | 8.2 | 8.2 | 8.2 | 8.2 | 0.1 | 0.2 | 1.0% | 2.1% |
| 20 | Composite | 8.4 | 8.3 | 8.5 | 8.3 | 8.5 | 0.1 | 0.2 | 0.9% | 2.1% |
| 30 | Concrete | 7.9 | 7.8 | 7.9 | 7.8 | 8.0 |  |  |  |  |
| 25 | Concrete | 8.1 | 8.0 | 8.1 | 8.1 | 8.1 |  |  |  |  |
| 20 | Concrete | 8.3 | 8.3 | 8.4 | 8.2 | 8.4 |  |  |  |  |

Shaded cells represent data that was not statistically significant

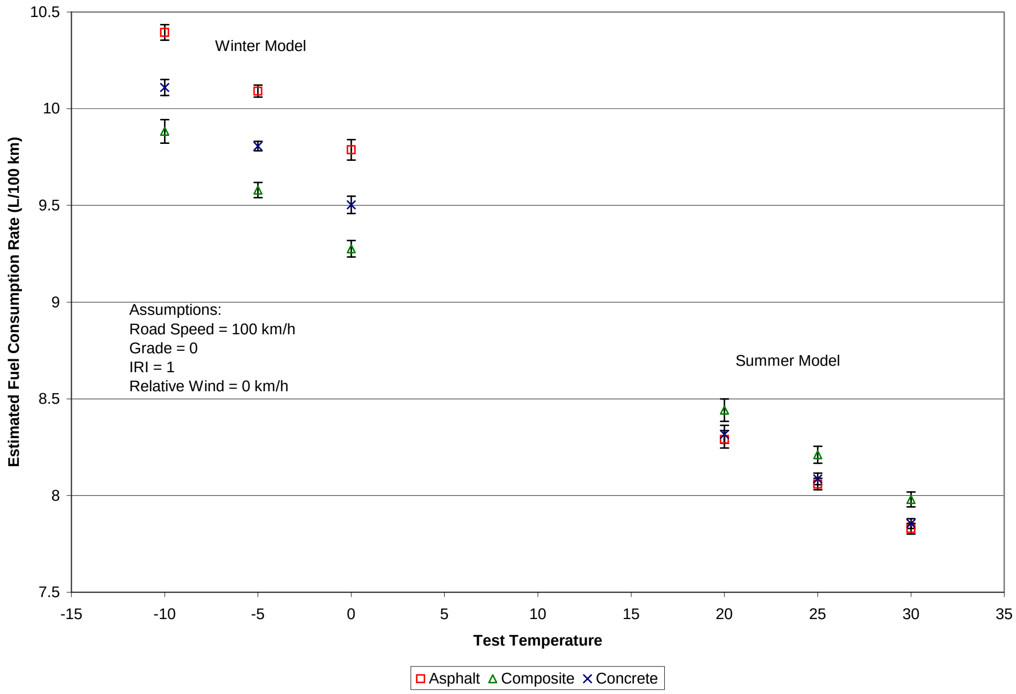

Figure 6-1 Car Point Estimates (-10 to 30 C)

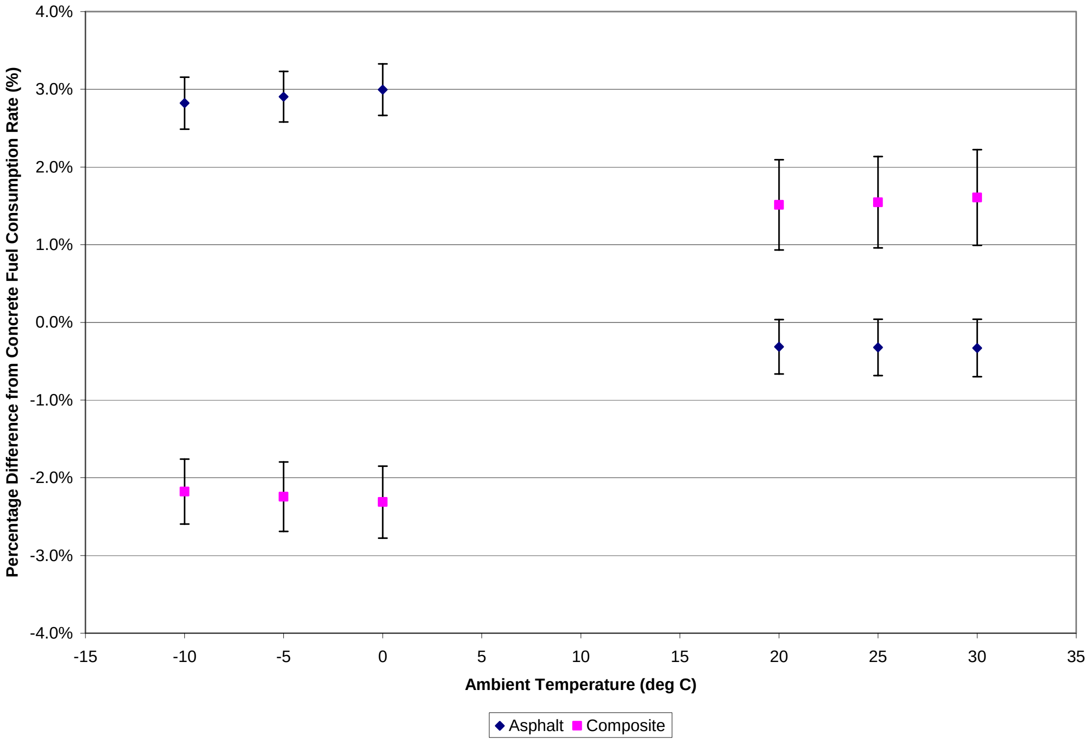

Figure 6-2 Car Percentage Change Estimates vs. Concrete, 100 km/h

From these model estimates the following conclusions can be made regarding the passenger vehicle testing:

- The point estimates for both the summer and winter models show excellent continuity and illustrate essentially the same linear relationship in both temperature ranges tested.

- All models have negative coefficients for pavement and ambient temperature and thus as the temperature increases the fuel consumption decreases.

- As illustrated in Figure 6-1, the winter model estimates that both the asphalt and the composite pavements are statistically different in energy requirements than the concrete.

- In the winter model, as shown in Figure 6-2, the composite pavements decreased the fuel requirements at –5C by 0.2 L/100km (2.1%) while the asphalt surfaces required an additional 0.3 L/100km (2.9%) fuel from the vehicle when compared to concrete. Both of these are statistically significant differences at the 95th percentile level;

- In the summer model (Figure 6-2), there is a 0.05 L/100km (0.3%) reduction in fuel consumption on asphalt when compared to concrete, however, this difference is not statistically significant.

- At 25 deg C there was a 0.1 L/100km (1.4%) increase in fuel consumption when driving over the composite pavements when compared to concrete roads. This difference was found to be statistically significant.

# 7 COMPARISON BETWEEN PHASES II AND III

## 7.1 Purpose

Upon delivery of a Draft Final report in January 2004, it became clear that the conclusions based on Phase III data differed from those of Phase II. NRCan and the Cement Association of Canada felt that this warranted additional analysis to resolve the basis for the differences. NRC/CSTT and its project partners were engaged to determine if the difference lay in the data, the models or the analyses. Although not part of the original scope of work, this Section attempts to explain the differences between the two Phases.

The following factors could have contributed to the differences:

- Poor data collection in either or both of the Phases (Section 6.2);
- Incorrect Model and/or analysis (Section 6.3);
- Different test conditions, parameters or road courses (Section 6.3).

In order to determine which of these factors caused the differences it was necessary to re-analyse the way in which the data were collected, review the methods that were used to analyse the data and review the various test conditions. In addition, it was felt that running the Phase II data in the Phase III model and running the Phase III data in the Phase II model could also shed some light on the issue.

## 7.2 Possibility of poor data collection in either of both of the phases

NRC/CSTT reviewed the way in which the data were collected and the parameters that were used to reject or accept data into the models. After considerable review CSTT/NRC has concluded that the raw data, the methodology used to gather the data and the filtering used to reject ‘out of range‘ data were not flawed. Although the roads and vehicles were different, the methodology did not vary significantly from previous phases.

Additionally, CSTT/NRC confirmed the sampling rate provided by the data acquisition system, performed a post test calibration of the wind speed anemometer and confirmed that the pre-determined weather parameters had not been exceeded.

## 7.3 Comparative Analysis of the Tanker semi-trailer (Phase II) and Van Semi-trailer (Phase III) Data

This section presents a comparison of the two most recent sets of semi-trailer test data, analyzed in two different ways. The first is the use of the regression models that were used in the Phase II rework analysis while the second uses the regression model developed in Phase III.

The total test program aimed at assessing the effect of pavement structure on vehicle fuel consumption was collected in two large sets of test data. The first set collected in Phase II was documented in a report entitled “Analysis of the Effect of Pavement Structure of Truck Fuel Consumption ” and statistically re-analyzed in the Phase II rework report titled “Additional Analysis of the Effect of Pavement Structure on Truck Fuel Consumption”.

These data were based on the use of tanker variants of a straight truck, semi-trailer and B-train vehicle configurations. In the Phase III set of data, a van style semi-trailer was used for the tests. Pavement test sites were selected in the Phase III tests on similar criteria and in many cases contained the same road sections as those in the Phase II test program but the Phase II sites had a wider range of pavement roughness such that the effect of roughness could be more discreetly measured.

### 7.3.1 Phase II Model

The Phase II data were collected on similar pavement types, but not necessarily the same locations as the Phase III tests. The vehicle used in the Phase II model analysis was a tanker semi-trailer which had a lower drag coefficient and was expected to minimize the effects of the aerodynamic drag forces and thus maximize the relative size and influence of the rolling forces.

The Phase II re-work multiple regression models were developed in such a way that fuel economy was specified to be a function of pavement structure, load, air temperature, pavement temperature, vehicle speed, wind speed, IRI, grade, and various interactions among these variables. Pavement structure was represented in the model by two indicator variables. The first took on a value of 1 for asphalt and 0 otherwise; the other a value of 1 for composite and 0 otherwise. Thus, concrete pavement was defined as the base category road type structure. Vehicle speed was also reflected by two indicator variables, with 60 km/hr set as the base category and 75 km/h and 100 km/h being discrete values. The results of this investigation suggested that the relative effects on fuel economy of air temperature, wind speed, and numerous variable interactions were small when compared to the remaining variables listed above. Thus, the model arising from the analysis was

$$\text{FUELCON(L/100km)} = \beta_0 + \beta_1\text{*PVASH} + \beta_2\text{*PVCOMP} + \beta_3\text{*LOAD} + \beta_4\text{*PAVETEMP} + \beta_5\text{*IRI} + \beta_6\text{*GRADE} + \beta 7\text{*SPEED75} + \beta_8\text{*SPEED100}$$

### 7.3.2 Phase III Model

The multiple regression analysis of the Phase III van semi-trailer data were undertaken in a slightly different manner than the Phase II model. This was due to an interest in having more engineering physics basis to the model form in which the speed terms would be included as continuous variables including measures of distance (1/v)[1], speed (v) and aerodynamic force ($v^2$). The pavement types were still used as indicator values.

$$\text{FUELCON(L/100km)} = \beta_0 + \beta_1\text{*PVASH} + \beta_2\text{*PVCOMP} + \beta_3\text{*LOAD} + \beta_4\text{*PAVETEMP} + \beta_5\text{*IRI} + \beta_6\text{*GRADE} + \beta 7\text{*SPEED} + \beta_8\text{*AIRSPDSQ} + \beta_{9*}\text{INVSPD}$$

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[1] Note that the comparative review model was modified slightly from the original Phase III model with the addition of the inverse of speed term. This was suggested in the external technical audit report by Sypher:Mueller International (A Review of the Report on Effects of Pavement Structure on Vehicle Fuel Consumption – Phase III, SYPHER:MUELLER International Inc., October 2004). The addition of the term improved the overall coefficient of determination by less than 1%.

### 7.3.3 Comparison of the Models and Data Sets

The analysis of the data was undertaken with the regression software package Minitab. Each dataset was run twice through the model, once using the Phase II model formulation and then with the Phase III formulation. In addition, two ranges for the IRI (international roughness index) were used within each data set. The first restricted IRI to less than 1.2 while the second set contained IRI values between 1.2 and 1.6. Although some of the data collected for Phase III were greater than 1.6, these values were rejected from the Phase III mathematical model as they were outside the pre-determined limits. As in Section 4.4, Tables 7-1 through 7-8 have been generated to display all the coefficients from the various models. These values were then used to generate the data presented in Tables 7-9 and 7-10.

### 7.3.4 Phase II Model Fit to Phase III Van Semi-trailer Data

The Phase II model, based on IRI less than 1.2, was developed using 46,624 observations. The regression equation estimated was:

FuelCon = 12.8 + 0.488 Pvash + 0.654 Pvcomp + 0.000091 Load - 0.0968 Pavetemp +
0.500 IRI + 14.9 Grade + 8.81 Spd75 + 22.4 Spd100

A coefficient of determination ($R^2$) for the model of 71.8% was obtained with all the variables statistically significant.

**Table 7-1 Phase II Model with Phase III data, IRI Less Than 1.2**

| **Predictor** | **Coef** | **SE Coef** | **$t_{ratio}$** | **$P_{value}$** |
|---|---|---|---|---|
| Constant | 12.7851 | 0.2466 | 51.84 | 0.000 |
| Pvash | 0.48776 | 0.07594 | 6.42 | 0.000 |
| Pvcomp | 0.6541 | 0.1129 | 5.79 | 0.000 |
| Load | 0.00009065 | 0.00000109 | 83.21 | 0.000 |
| Pavetemp | -0.096766 | 0.002039 | -47.45 | 0.000 |
| IRI | 0.4999 | 0.2125 | 2.35 | 0.019 |
| Grade | 14.8676 | 0.0831 | 178.88 | 0.000 |
| Spd75 | 8.80955 | 0.07459 | 118.11 | 0.000 |
| Spd100 | 22.4238 | 0.0809 | 277.27 | 0.000 |
| $R^2$ = 71.8%, n=46,624 observations | | | | |

The IRI data between 1.2 and l.6 contained 27,033 observations and estimated the following equation which had a $R^2$ of 67.7%.

FuelCon = 13.1 + 0.711 Pvash - 0.402 Pvcomp + 0.000089 Load - 0.0774 Pavetemp +
0.088 IRI + 15.0 Grade + 9.11 Spd75 + 22.5 Spd100

**Table 7-2 Phase II Model with Phase III data, IRI between 1.2 And 1.6**

| Predictor | Coef | SE Coef | $t_{ratio}$ | $P_{value}$ |
|---|---|---|---|---|
| Constant | 13.1375 | 0.5983 | 21.96 | 0.000 |
| Pvash | 0.7108 | 0.1032 | 6.89 | 0.000 |
| Pvcomp | -0.4024 | 0.2548 | -1.58 | 0.114 |
| Load | 0.00008870 | 0.00000162 | 54.82 | 0.000 |
| Pavetemp | -0.077372 | 0.003049 | -25.37 | 0.000 |
| IRI | 0.0879 | 0.4260 | 0.21 | 0.837 |
| Grade | 14.9646 | 0.1199 | 124.85 | 0.000 |
| Spd75 | 9.1075 | 0.1125 | 80.93 | 0.000 |
| Spd100 | 22.5353 | 0.1166 | 193.29 | 0.000 |
| $R^2$ = 67.7%, n=27,033 observations | | | | |

### 7.3.5 Phase III Model Fit to Van Semi-trailer Data

The Phase III model results, while providing different coefficients for some common variables between the models, had very similar $R^2$ to the Phase II model.

For IRI less than 1.2 (46,624 observations), the regression equation was:

FuelCon = - 68.5 + 0.469 Pvash + 0.267 Pvcomp + 0.000093 Load - 0.0968 Pavetemp + 0.532 IRI + 15.0 Grade + 0.713 Speed + 0.00130 AirSpdSq + 2068 InvSpd

**Table 7-3 Phase III Model with Phase III data, IRI Less Than 1.2**

| Predictor | Coef | SE Coef | $t_{ratio}$ | $P_{value}$ |
|---|---|---|---|---|
| Constant | -68.482 | 2.307 | -29.69 | 0.000 |
| Pvash | 0.46883 | 0.07604 | 6.17 | 0.000 |
| Pvcomp | 0.2673 | 0.1134 | 2.36 | 0.018 |
| Load | 0.00009252 | 0.00000109 | 84.81 | 0.000 |
| Pavetemp | -0.096841 | 0.002040 | -47.47 | 0.000 |
| IRI | 0.5322 | 0.2126 | 2.50 | 0.012 |
| Grade | 15.0491 | 0.0831 | 181.05 | 0.000 |
| Speed | 0.71286 | 0.01651 | 43.18 | 0.000 |
| AirSpdSq | 0.00129913 | 0.00003763 | 34.53 | 0.000 |
| InvSpd | 2067.57 | 84.42 | 24.49 | 0.000 |
| $R^2$ = 71.8%, n=46,624 observations | | | | |

The data with an IRI of at least 1.2 and less than 1.6 (27,033 observations) provided a regression equation of

FuelCon = - 58.6 + 0.772 Pvash + 0.429 Pvcomp + 0.000094 Load - 0.0817 Pavetemp + 0.080 IRI + 15.0 Grade + 0.629 Speed + 0.00151 AirSpdSq + 1743 InvSpd

**Table 7-4 Phase III Model with Phase III data, IRI between 1.2 And 1.6**

| Predictor | Coef | SE Coef | $t_{ratio}$ | $P_{value}$ |
|---|---|---|---|---|
| Constant | -58.598 | 3.529 | -16.61 | 0.000 |
| Pvash | 0.7722 | 0.1033 | 7.47 | 0.000 |
| Pvcomp | 0.4288 | 0.2569 | 1.67 | 0.095 |
| Load | 0.00009382 | 0.00000163 | 57.66 | 0.000 |
| Pavetemp | -0.081705 | 0.003054 | -26.75 | 0.000 |
| IRI | 0.0804 | 0.4263 | 0.19 | 0.850 |
| Grade | 14.9721 | 0.1202 | 124.56 | 0.000 |
| Speed | 0.62938 | 0.02446 | 25.73 | 0.000 |
| AirSpdSq | 0.00151453 | 0.00005304 | 28.56 | 0.000 |
| InvSpd | 1742.6 | 127.2 | 13.70 | 0.000 |
| $R^2$ = 67.6% , n=27,033 observations | | | | |

### 7.3.6 Phase II Model Fit to Phase II Tanker Semi-trailer Data

The Phase II data for IRIs less than 1.2 produced a regression equation of:

FuelCon = 17.2 + 1.76 Pvash + 1.18 Pvcomp + 0.000295 Load - 0.156 Pavetemp + 2.33 IRI + 737 Grade + 3.87 Spd75 + 10.3 Spd100

In this case, the $R^2$ is marginally lower (59.5%) than the Phase II model but still quite an acceptable value given the large number of observations (22,678).

**Table 7-5 Phase II Model with Phase II data, IRI Less Than 1.2**

| Predictor | Coef | SE Coef | $t_{ratio}$ | $P_{value}$ |
|---|---|---|---|---|
| Constant | 17.1533 | 0.2362 | 72.63 | 0.000 |
| Pvash | 1.7637 | 0.1072 | 16.46 | 0.000 |
| Pvcomp | 1.1755 | 0.1106 | 10.63 | 0.000 |
| Load | 0.00029459 | 0.00000342 | 86.02 | 0.000 |
| Pavetemp | -0.155534 | 0.001903 | -81.74 | 0.000 |
| IRI | 2.3326 | 0.1887 | 12.36 | 0.000 |
| Grade | 736.97 | 14.42 | 51.11 | 0.000 |
| Spd75 | 3.87459 | 0.07080 | 54.72 | 0.000 |
| Spd100 | 10.2833 | 0.0779 | 131.94 | 0.000 |
| $R^2$ = 59.6%, n=22,678 observations | | | | |

For road sections with an IRI of at least 1.2 and less than 1.6, the model fit was slightly lower than for the smoother sections at an $R^2$ of 54.7% and a regression equation of:

FuelCon = 17.9 + 1.80 Pvash + 0.805 Pvcomp + 0.000310 Load - 0.148 Pavetemp + 1.13 IRI + 330 Grade + 4.03 Spd75 + 10.4 Spd100

**Table 7-6 Phase II Model with Phase II data, IRI Between 1.2 And 1.6**

| Predictor | Coef | SE Coef | $t_{ratio}$ | $P_{value}$ |
|---|---|---|---|---|
| Constant | 17.8796 | 0.5553 | 32.20 | 0.000 |
| Pvash | 1.7973 | 0.1175 | 15.30 | 0.000 |
| Pvcomp | 0.8054 | 0.1192 | 6.76 | 0.000 |
| Load | 0.00031042 | 0.00000482 | 64.36 | 0.000 |
| Pavetemp | -0.148435 | 0.002545 | -58.32 | 0.000 |
| IRI | 1.1250 | 0.3874 | 2.90 | 0.004 |
| Grade | 329.86 | 17.20 | 19.17 | 0.000 |
| Spd75 | 4.03412 | 0.09936 | 40.60 | 0.000 |
| Spd100 | 10.3752 | 0.1066 | 97.29 | 0.000 |
| $R^2$ = 54.7%, n=14,772 observations | | | | |

### 7.3.7 Phase III Model Fit To Phase II Tanker Semi-trailer Data

The 2003 model, for IRI ranges less than 1.2, had a very similar $R^2$ to the Phase II model of 58.5%. The regression equation was:

FuelCon = - 29.1 + 1.90 Pvash + 1.15 Pvcomp + 0.000297 Load - 0.155 Pavetemp + 2.37 IRI + 748 Grade + 0.441 Speed + 0.000039 AirSpdSq + 1196 InvSpd

**Table 7-7 Phase III Model with Phase II data, IRI Less Than 1.2**

| Predictor | Coef | SE Coef | $t_{ratio}$ | $P_{value}$ |
|---|---|---|---|---|
| Constant | -29.057 | 1.499 | -19.38 | 0.000 |
| Pvash | 1.8966 | 0.1140 | 16.64 | 0.000 |
| Pvcomp | 1.1534 | 0.1170 | 9.86 | 0.000 |
| Load | 0.00029732 | 0.00000356 | 83.50 | 0.000 |
| Pavetemp | -0.154658 | 0.001979 | -78.13 | 0.000 |
| IRI | 2.3744 | 0.1964 | 12.09 | 0.000 |
| Grade | 748.16 | 15.05 | 49.70 | 0.000 |
| Speed | 0.44143 | 0.01198 | 36.84 | 0.000 |
| AirSpdSq | 0.00003857 | 0.00003286 | 1.17 | 0.240 |
| InvSpd | 1195.96 | 53.72 | 22.26 | 0.000 |
| $R^2$ = 58.5%, n=22,039 observations | | | | |

Similarly, test data with IRIs of at least 1.2 and less than 1.6 provided a model with an $R^2$ of 53.9%.

FuelCon = - 22.4 + 1.91 Pvash + 0.963 Pvcomp + 0.000311 Load - 0.149 Pavetemp + 1.14 IRI + 342 Grade + 0.390 Speed + 0.000177 AirSpdSq + 1001 InvSpd

**Table 7-8 Phase III Model with Phase II data, IRI between 1.2 And 1.6**

| **Predictor** | **Coef** | **SE Coef** | $t_{ratio}$ | $P_{value}$ |
|---|---|---|---|---|
| Constant | -22.397 | 2.196 | -10.20 | 0.000 |
| Pvash | 1.9054 | 0.1218 | 15.64 | 0.000 |
| Pvcomp | 0.9632 | 0.1293 | 7.45 | 0.000 |
| Load | 0.00031061 | 0.00000492 | 63.16 | 0.000 |
| Pavetemp | -0.149181 | 0.002680 | -55.67 | 0.000 |
| IRI | 1.1400 | 0.3964 | 2.88 | 0.004 |
| Grade | 341.95 | 17.67 | 19.35 | 0.000 |
| Speed | 0.38978 | 0.01720 | 22.67 | 0.000 |
| AirSpdSq | 0.00017685 | 0.00005040 | 3.51 | 0.000 |
| InvSpd | 1000.60 | 73.98 | 13.53 | 0.000 |
| $R^2$ = 53.9%, n=14,223 observations | | | | |

### 7.3.8 Comparisons

In comparing the Phase II models with the Phase III models, it is clear that both formulations provide very similar coefficient of determinations. This means that either model has essentially the same accuracy of prediction. In both models, the predictive accuracy is higher with the lower range of IRI values.

To more easily compare the two model formulations, point estimates were developed from each equation set under a number of standard conditions (temperature =25 deg C, grade=0, relative wind=0) with the load and speed varying. For the low IRI models, the point estimate was made with an IRI value of 1.0 while for the higher IRI model the IRI was fixed at 1.5. The output of these estimates is provided in Table 7-9 for the van semi trailer data (Phase III) and in Table 7-10 for the tanker semi trailer data (Phase II).

The absolute differences in fuel consumption from a concrete reference for the asphalt and composite pavements were calculated as well as the percentage differences. The statistical significance of the differences were also assessed at the 95th percentile level (non-significant differences are shaded). The tables reveal the following findings:

- The Phase III model consistently predicts a higher fuel consumption rate for all the load, speed and pavement conditions than the Phase II model.
- For the van semi trailer data (Phase III), the composite pavements were not significantly different from the concrete for all load, speed and road roughness condition, except for the Phase II model estimates, with low IRI values.
- In all the load, speed and roughness value conditions, the van model (Phase III) estimated that the asphalt pavements produced statistically significantly higher fuel consumption than the concrete pavements.
- For the tanker semi trailer models (Phase II), all the differences between concrete and both asphalt and composite are statistically significant at the 95th percentile with absolute difference estimates of 1.2 and 1.9 L/100km for the composite and asphalt pavements respectively.

- Both models provide constant absolute change estimates, independent of vehicle speed and load.

For the Phase III van semi trailer data:

- The Phase III model estimates the absolute difference for the low IRI model as 0.3 L/100km for the composite pavement (significant) and 0.5 L/100km (significant) for the asphalt;
- The Phase II model estimates significant differences of 0.7 and 0.5 L/100km for the composite and asphalt pavements respectively;
- For the rougher IRI range at 1.5, the asphalt was predicted to have a 0.8 L/100km increase and the composite a not-significant 0.4 L/100km increase using the Phase III model;
- The Phase II model predicted a –0.4 L/100km (not-significant) change for the composite pavement and a 0.7 L/100km (significant) change on the asphalt.
- The largest overall percentage difference for the Phase III van data was 5.2%, which was recorded on rougher roads and with an empty trailer. The lowest percentage difference was 1.1% which was recorded on smoother roads with the maximum payload.

For the Phase II tanker data:

- The absolute difference estimates were higher than the van semi trailer and all differences were statistically significant at the 95th percentile level;
- With the Phase III model at an IRI of 1.0, a difference of 1.2 and 1.9 L/100km for composite and asphalt pavements was estimated while the Phase II tanker model had estimates of 1.2 and 1.8 L/100km, at an IRI of 1.5;
- The Phase III model differences were 1.0 and 1.9 L/100km for composite and asphalt and using the Phase II tanker model, the differences were 0.8 and 1.8 L/100km for composite and asphalt respectively.

The insensitivity of the fuel consumption differences to temperature, load and speed is somewhat counterintuitive to the engineering physical models. As a result, additional statistical tests were undertaken on the data to assure that the models were not missing interaction terms which measure the possibility that the relationship between fuel consumption and pavement type is different for different speeds, or for different loads. In all cases the inclusion of the interaction terms had no effect on the value of " $R^2$", the coefficient of determination for the model which measures the overall fit of the model to the data. The interactive terms are thus very minor compared to the other variables included in this model.

Additionally, the constant nature of the absolute differences means that as the vehicle's fuel consumption rate increases with load and speed, the percentage differences decrease as the load and speed increase. At 25 deg C on smooth roads (IRI= 1.0), the tanker semi trailer's (Phase II) maximum percent differences of 9.2% (1.9 L/100km) and 5.5% (1.2 L/100km) in concrete's favour with respect to asphalt and composite respectively and were at 60 km/h in an empty condition. The van semi trailer (Phase III) had its highest percent difference of 3.2% (0.5 L/100km) in favour of concrete relative to asphalt at the same conditions at an IRI value of 1.0. However, the differences relative to composite for IRI values of 1.5 were not statistically significant.

The smallest percentage changes were calculated at 100 km/h with the maximum legal load and were 1.1% (0.5 L/100km) for the van semi trailer (Phase III) on asphalt and 4.3% (1.8 L/100km) and 1.9% (0.8 L/100km) for the tanker semi trailer (Phase II) on asphalt and composite pavements respectively. All these differences were statistically significant.

The point estimates for the “full” load (43,660 kg or 96,000 lb.) at a speed of 100 km/h from the tables are shown graphically in Figures 7-1 through 7-4. These plot the mean estimate and the 95th percentile confidence bounds for each of the point estimates of fuel consumption against test temperature. Both the Phase II and the Phase III models estimates are presented in each graph. The fact that the Phase III model produces higher absolute fuel consumption estimates than the Phase II model can be seen on the graphs.

## Table 7-9 Comparison of Phase III data (van) in Phase III and Phase II Models, at 25 deg C

| Phase III Data and Phase III Model | Conditions: Temp=25 deg C, Grade=0, Rel Wind=0 | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Load | Empty 36,000 lb/ 16,329 kg | | | | | | | Typical Full 96,000 lb/ 43,660 kg | | | | | | | Maximum 109,000 lb/ 49,441 kg | | | | | | |
| | Model Mean Estimate (L/100km) | | | Absolute Difference | | Percentage Difference | | Model Mean Estimate (L/100km) | | | Absolute Difference | | Percentage Difference | | Model Mean Estimate (L/100km) | | | Absolute Difference | | Percentage Difference | |
| Speed (km/h) | Concrete | Comp-osite | Asphalt | Com-Con | Asp-Con | Com-Con | Asp-Con | Concrete | Comp osite | Asphalt | Com-Con | Asp-Con | om-Con | Asp-Con | Concrete | Comp-osite | Asphalt | Com-Con | Asp-Con | Com-Con | Asp-Con |
| IRI=1.0 | | | | | | | | | | | | | | | | | | | | | |
| 60 | 14.9 | 15.1 | 15.3 | 0.3 | 0.5 | **1.9%** | **3.2%** | 20.4 | 20.7 | 20.9 | 0.3 | 0.5 | 1.4% | 2.4% | 21.6 | 21.9 | 22.1 | 0.3 | 0.5 | 1.3% | 2.2% |
| 75 | 21.3 | 21.6 | 21.8 | 0.3 | 0.5 | 1.3% | 2.3% | 26.9 | 27.1 | 27.3 | 0.3 | 0.5 | 1.1% | 1.8% | 28.1 | 28.3 | 28.5 | 0.3 | 0.5 | 1.0% | 1.7% |
| 100 | 37.9 | 38.2 | 38.4 | 0.3 | 0.5 | 0.7% | 1.3% | 43.5 | 43.7 | 43.9 | 0.3 | 0.5 | 0.6% | 1.1% | 44.7 | 44.9 | 45.1 | 0.3 | 0.5 | **0.6%** | **1.1%** |
| | | | | | | | | | | | | | | | | | | | | | |
| IRI=1.5 | | | | | | | | | | | | | | | | | | | | | |
| 60 | 15.1 | 15.5 | 15.9 | 0.4 | 0.8 | 2.8% | **5.2%** | 20.7 | 21.2 | 21.5 | 0.4 | 0.8 | 2.2% | 3.8% | 22.0 | 22.4 | 22.7 | 0.4 | 0.8 | 2.1% | 3.5% |
| 75 | 21.8 | 22.2 | 22.6 | 0.4 | 0.8 | 2.1% | 3.6% | 27.4 | 27.9 | 28.2 | 0.4 | 0.8 | 1.7% | 2.9% | 28.7 | 29.1 | 29.4 | 0.4 | 0.8 | 1.6% | 2.7% |
| 100 | 38.4 | 38.8 | 39.1 | 0.4 | 0.8 | 1.1% | 2.1% | 44.0 | 44.4 | 44.8 | 0.4 | 0.8 | 1.1% | 1.8% | 45.2 | 45.6 | 46.0 | 0.4 | 0.8 | 1.0% | **1.7%** |
| | | | | | | | | | | | | | | | | | | | | | |
| **Phase III data and Phase II Model Conditions: Temp=25 deg C, Grade=0, Rel Wind=0** | | | | | | | | | | | | | | | | | | | | | |
| IRI=1.0 | | | | | | | | | | | | | | | | | | | | | |
| 60 | 14.1 | 14.8 | 14.6 | 0.7 | 0.5 | **4.8%** | **3.5%** | 19.6 | 20.2 | 20.1 | 0.7 | 0.5 | 3.4% | 2.5% | 20.7 | 21.4 | 21.2 | 0.7 | 0.5 | 3.2% | 2.4% |
| 75 | 22.9 | 23.6 | 23.4 | 0.7 | 0.5 | 2.9% | 2.2% | 28.4 | 29.0 | 28.9 | 0.7 | 0.5 | 2.4% | 1.8% | 29.6 | 30.2 | 30.0 | 0.7 | 0.5 | 2.3% | 1.7% |
| 100 | 36.6 | 37.2 | 37.0 | 0.7 | 0.5 | 1.8% | 1.4% | 42.0 | 42.6 | 42.5 | 0.7 | 0.5 | **1.6%** | 1.2% | 43.2 | 43.8 | 43.7 | 0.7 | 0.5 | 1.6% | 1.2% |
| | | | | | | | | | | | | | | | | | | | | | |
| IRI=1.5 | | | | | | | | | | | | | | | | | | | | | |
| 60 | 14.5 | 14.1 | 15.2 | -0.4 | 0.7 | -2.6% | 4.9% | 19.9 | 19.4 | 20.6 | -0.4 | 0.7 | -2.0% | 3.7% | 22.0 | 22.4 | 22.7 | -0.4 | 0.8 | -1.7% | 3.3% |
| 75 | 23.6 | 23.2 | 24.3 | -0.4 | 0.7 | -1.6% | 3.0% | 29.0 | 28.6 | 29.7 | -0.4 | 0.7 | -1.4% | 2.5% | 30.1 | 29.7 | 30.8 | -0.4 | 0.7 | -1.2% | 2.4% |
| 100 | 37.1 | 36.7 | 37.8 | -0.4 | 0.7 | -1.1% | 1.9% | 42.4 | 42.0 | 43.1 | -0.4 | 0.7 | -0.9% | 1.7% | 43.5 | 43.1 | 44.2 | -0.4 | 0.7 | -0.9% | **1.7%** |

Shaded cells indicate non-significant differences at 95th percentile confidence bounds

## Table 7-10 Comparison of Phase II Data (tanker) in Phase II and Phase III Models, at 25 deg C

| **Phase II data in Phase III Model** | **Conditions: Temp=25 deg C, Grade=0, Rel Wind=0** | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Load** | **Empty<br>36,000 lb/ 16,329 kg** | | | | | | | **Typical Full<br>96,000 lb/ 43,660 kg** | | | | | | | **Maximum<br>109,000 lb/ 49,441 kg** | | | | | | |
| | **Model Mean Estimate (L/100 km)** | | | **Absolute Difference** | | **Percentage Difference** | | **Model Mean Estimate (L/100 km)** | | | **Absolute Difference** | | **Percentage Difference** | | **Model Mean Estimate (L/100 km)** | | | **Absolute Difference** | | **Percentage Difference** | |
| Speed (km/h) | Concrete | Composite | Asphalt | Com-Con | Asp-Con | Com-Con | Asp-Con | Concrete | Composite | Asphalt | Com-Con | Asp-Con | Com-Con | Asp-Con | Concrete | Composite | Asphalt | Com-Con | Asp-Con | Com-Con | Asp-Con |
| IRI=1.0 | | | | | | | | | | | | | | | | | | | | | |
| 60 | 20.9 | 22.0 | 22.8 | 1.2 | 1.9 | 5.5% | **9.2%** | 29.0 | 30.1 | 30.9 | 1.2 | 1.9 | 4.0% | 6.6% | 30.7 | 31.9 | 32.6 | 1.2 | 1.9 | 3.8% | 6.2% |
| 75 | 23.6 | 24.7 | 25.5 | 1.2 | 1.9 | 4.9% | 8.1% | 31.7 | 32.8 | 33.6 | 1.2 | 1.9 | 3.6% | 6.0% | 33.4 | 34.6 | 35.3 | 1.2 | 1.9 | 3.5% | 5.7% |
| 100 | 30.8 | 32.0 | 32.7 | 1.2 | 1.9 | 3.8% | 6.2% | 38.9 | 40.1 | 40.8 | 1.2 | 1.9 | 3.0% | 4.9% | 40.7 | 41.8 | 42.5 | 1.2 | 1.9 | 2.7% | 4.7% |
| | | | | | | | | | | | | | | | | | | | | | |
| IRI=1.5 | | | | | | | | | | | | | | | | | | | | | |
| 60 | 21.4 | 22.3 | 23.3 | 1.0 | 1.9 | 4.6% | 8.9% | 29.8 | 30.8 | 31.7 | 1.0 | 1.9 | 3.2% | 6.4% | 31.7 | 32.6 | 33.6 | 1.0 | 1.9 | 3.1% | 6.1% |
| 75 | 24.2 | 25.2 | 26.1 | 1.0 | 1.9 | 4.1% | 7.9% | 32.7 | 33.7 | 34.6 | 1.0 | 1.9 | 2.9% | 5.8% | 34.5 | 35.5 | 36.4 | 1.0 | 1.9 | 2.8% | 5.6% |
| 100 | 31.4 | 32.4 | 33.3 | 1.0 | 1.9 | 3.1% | 6.1% | 39.9 | 40.8 | 41.8 | 1.0 | 1.9 | 2.4% | 4.8% | 41.7 | 42.7 | 43.6 | 1.0 | 1.9 | 2.4% | **4.6%** |
| | | | | | | | | | | | | | | | | | | | | | |
| **Phase II data in Phase II model Conditions: Temp=25 deg C, Grade=0, Rel Wind=0** | | | | | | | | | | | | | | | | | | | | | |
| IRI=1.0 | | | | | | | | | | | | | | | | | | | | | |
| 60 | 20.4 | 21.6 | 22.2 | 1.2 | 1.8 | **5.8%** | **8.7%** | 28.4 | 29.6 | 30.2 | 1.2 | 1.8 | 4.1% | 6.2% | 30.2 | 31.4 | 31.9 | 1.2 | 1.8 | 3.9% | 5.8% |
| 75 | 24.3 | 25.5 | 26.1 | 1.2 | 1.8 | 4.8% | 7.3% | 32.3 | 33.5 | 34.1 | 1.2 | 1.8 | 3.6% | 5.5% | 34.1 | 35.2 | 35.8 | 1.2 | 1.8 | 3.5% | 5.2% |
| 100 | 30.7 | 31.9 | 32.5 | 1.2 | 1.8 | 3.8% | 5.7% | 38.7 | 39.9 | 40.5 | 1.2 | 1.8 | 3.0% | 4.6% | 40.5 | 41.6 | 42.2 | 1.2 | 1.8 | 2.9% | 4.4% |
| | | | | | | | | | | | | | | | | | | | | | |
| IRI=1.5 | | | | | | | | | | | | | | | | | | | | | |
| 60 | 20.9 | 21.7 | 22.7 | 0.8 | 1.8 | 3.8% | 8.7% | 29.4 | 30.2 | 31.2 | 0.8 | 1.8 | 2.7% | 6.1% | 31.2 | 32.0 | 33.0 | 0.8 | 1.8 | 2.6% | 5.8% |
| 75 | 25.0 | 25.8 | 26.8 | 0.8 | 1.8 | 3.2% | 7.3% | 33.4 | 34.2 | 35.2 | 0.8 | 1.8 | 2.4% | 5.4% | 35.3 | 36.1 | 37.0 | 0.8 | 1.8 | 2.3% | 5.1% |
| 100 | 31.3 | 32.1 | 33.1 | 0.8 | 1.8 | 2.6% | 5.7% | 39.8 | 40.6 | 41.6 | 0.8 | 1.8 | 2.0% | 4.5% | 41.6 | 42.4 | 43.4 | 0.8 | 1.8 | **1.9%** | **4.3%** |

Shaded cells indicate non-significant differences at 95th percentile confidence bounds

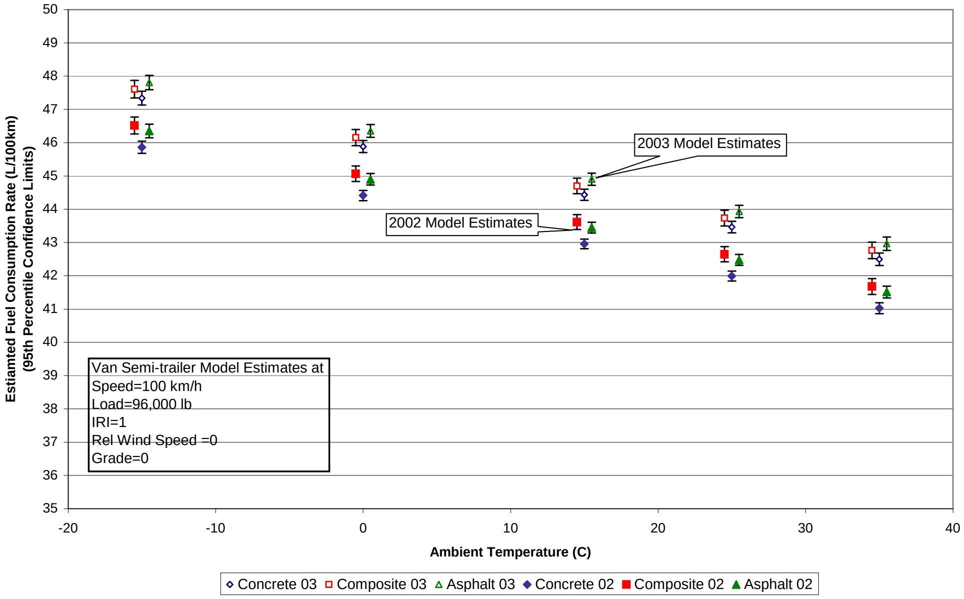


Figure 7-1 Van Model Comparisons at 100 km/h and IRI=1.0

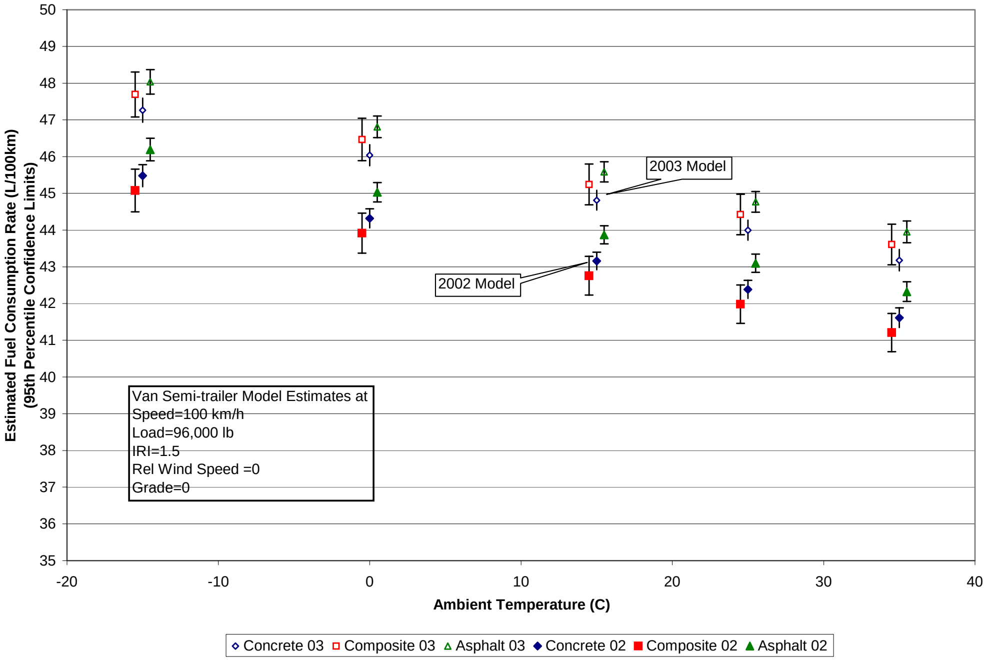
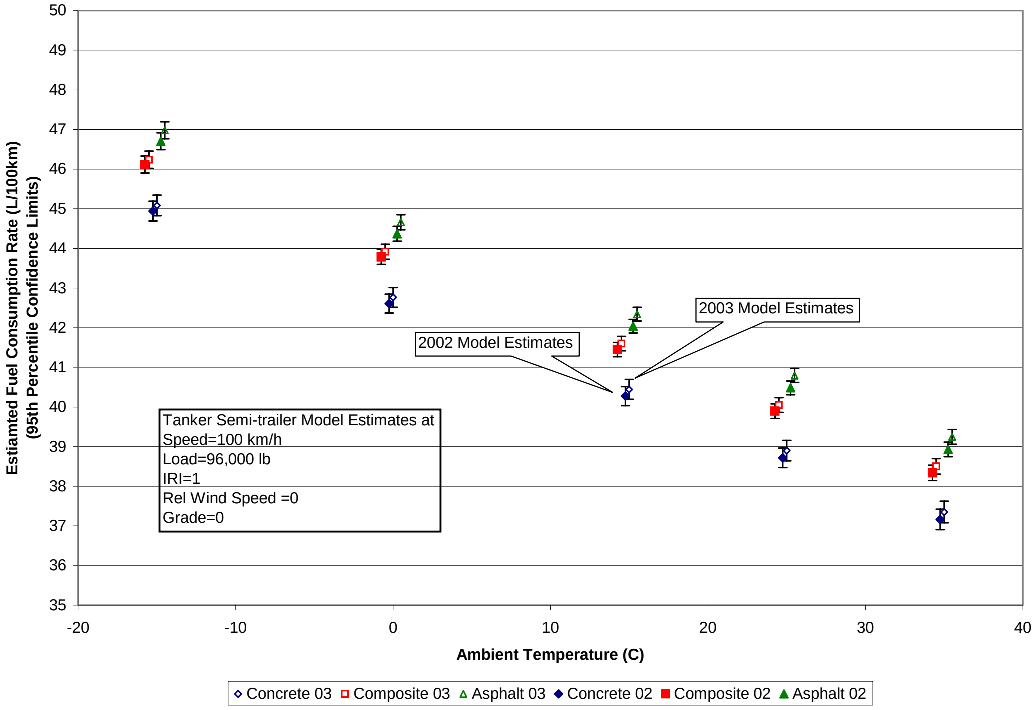
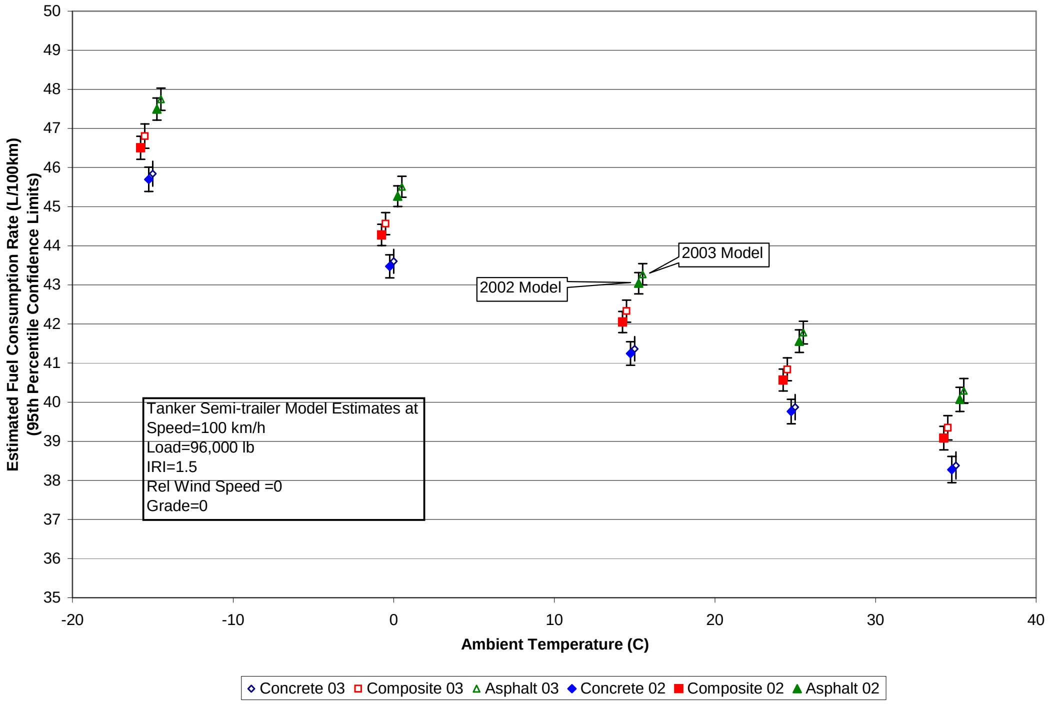


Figure 7-2 Van Model Comparisons at 100 km/h and IRI=1.5



Tanker Semi-trailer Model Estimates at
Speed=100 km/h
Load=96,000 lb
IRI=1
Rel Wind Speed =0
Grade=0

**Figure 7-3 Tanker Model Comparions at 100 km/h and IRI=1.0**



Tanker Semi-trailer Model Estimates at
Speed=100 km/h
Load=96,000 lb
IRI=1.5
Rel Wind Speed =0
Grade=0

**Figure 7-4 Tanker Model Comparisons at 100 km/h and IRI=1.5**

# 8 SUMMARY OF FINDINGS

From the testing undertaken as part of this study, the following observations are made:

## 8.1 2003 Van Semi-trailer Tests

1. The testing of a tractor/tridem van semi-trailer was successfully completed over a variety of test sites composed of concrete, asphalt, and composite (concrete with an asphalt top coat) in temperature conditions ranging from –20 deg C to +34 deg C;

2. Given the immense amount of data, the models for each seasonal truck data set and also the total combined truck data set provided good coefficients of determination with values between 66% and 78%;

3. The Phase III (van semi-trailer) multiple regression was used to estimate fuel consumption rates on the various pavements at temperatures from –20 deg C to +35 deg C and assuming 0% grade, IRI =1, relative wind = 0 km/h, and loads of 16,000, 46,500, and 49,400kg.

4. At 100 km/h, the results showed a mean percentage difference favouring concrete roads (i.e. reduced fuel consumption) when compared to asphalt pavements. The value of the fuel savings ranged from 0.8% to 1.8% and these results were all statistically significant with the exception of the Summer Night data, at 0.4% (Figure 4-4).

5. At 100 km/h, the concrete roads performed better than composite roads in four of the five seasons with savings as low as 0.8% and as high as 3.1%. These differences were all statistically significant with the exception of the spring data. However, at all loading conditions the composite pavements were found to be 1.5% more fuel efficient than the concrete roads for summer day conditions. This difference was statistically significant (Figure 4-5).

6. 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. Figure 4-12.

7. The fuel savings for the full trailer at 60 km/h when comparing concrete to asphalt roads ranged from 0.2 L/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. Figure 4-13.

8. 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. Figure 4-14.

9. 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**.** Figure 4-15.

## 8.2 Coastdown Tests

1. The test results were analysed by means of a multiple regression model which allowed for the estimation of each independent variable's (rolling resistance (time), wind speed, grade, and curvature) coefficient to be measured. Comparing the rolling resistance (time) coefficient of concrete to the other pavements does not indicate any consistent differences between pavement types.

## 8.3 Passenger Vehicle Tests

1. The point estimates for both the summer and winter models show excellent continuity and illustrate essentially the same linear relationship in both temperature ranges tested.

2. Due to the limited number of data points and seasonal conditions, the results from the passenger car testing were less conclusive than the tractor and trailer testing.

3. Of the four seasonal car models presented below, three were statistically significant and one was not (asphalt versus concrete in summer).

4. In winter testing, the passenger car consumed 0.3 L/100 km more (2.9%) on asphalt than on concrete. These savings were all statistically significant.

5. In winter testing, the car consumed 0.2 L/100 km less fuel (2.3%) on composite pavement when compared to concrete. These savings were all statistically significant.

6. In summer testing, the passenger car consumed 0.1 L/100 km (1.5%) more fuel on composite roads when compared to concrete. These savings were all statistically significant.

7. In summer testing, the passenger car consumed 0.05 L/100 km (0.3%) less fuel on asphalt roads when compared to concrete. However, these savings were not statistically significant.

## 8.4 Phase II to Phase III Model Comparison

1. The comparison of the two sets of test data from the Phase III (van semi-trailer) and Phase II (tanker semi-trailer) was successfully undertaken using two different regression models

and indicated that the two model formulations produced very similar results in terms of their explanatory power expressed as the coefficient of determination ($R^2$).

2. The individual variables in each model were all measured to be significant in both data sets.

3. Point estimates made using both models for both vehicle types at a series of standard conditions indicated that fuel consumption of the vehicle was consistently lower on concrete than on asphalt or composite pavement types.

4. The absolute differences in fuel consumption of the vehicles driving on asphalt and composite pavements respective to concrete pavements were constant with respect to load, speed and temperature conditions.

5. The fuel consumption rate of both vehicle types on asphalt pavement, relative to concrete, was statistically significantly higher using both models and in both IRI ranges (less than 1.2, and 1.2 to1.6).

6. The differences on the asphalt pavement compared to concrete were constant (in absolute L/100km) with respect to temperature, speed and load and ranged between 0.5 L/100 km (1.1% to 3.5%) for smooth pavements (IRI = 1.0) and 0.8 L/100 km (1.7% to 5.2%) for pavements with an IRI of 1.5 for the Phase III (van semi trailer) data in each of the models (Table 7-9). All these differences were statistically significant and in concrete's favour.

7. The differences on the asphalt pavement compared to concrete for the Phase II data (tanker semi-trailer) using the Phase III model (van semi-trailer) were 1.9 L/100 km (4.7 to 9.2%) for both smooth (IRI = 1.0) and rougher roads (IRI = 1.5). The differences for the Phase II data using the Phase II model were 1.8 L/100km (4.3% to 8.7%) for both smooth and rougher roads. All these differences were statistically significant and in concrete's favour (Table 7-10).

8. The fuel consumption rate on composite pavement, when compared to concrete, was statistically significantly higher using both models and in both IRI ranges (lRI = 1.0 and 1.5) for the Phase II data. The value of this difference was between 0.8 L/100km and 1.2 L/100km (1.9% to 5.8%) (Table 7-10).

9. For the Phase III data (van semi trailer) on smooth roads (IRI = 1.0) the fuel savings were statistically significant in concrete's favour relative to composite, and were estimated using both models to be 0.7 L/100km difference (1.6% to 4.8%) in the Phase II model (tanker semi-trailer) and 0.3 L/100km in the Phase III model (0.6% to 1.9%). The values on rougher roads (IRI = 1.5) for the Phase III data were not statistically significant in either of the models (Table 7-9).

# 9 CONCLUSIONS

The testing of typical van style heavy goods trailer and passenger car on a variety of pavement structures including concrete, asphalt and composite (concrete with an asphalt top coat) was completed over temperatures representing a complete annual range of operating seasons in Eastern Canada. From this testing, the following conclusions have been formulated and relate to the specific sections of roads tested as part of the Phase III programme:

1. The effects of load and rolling resistance in the summer night model appear to be much less than those seen in the other models. It is therefore likely that no conclusions can be drawn from the summer night data and corresponding model.

2. The Phase III multi regression analysis models (winter, spring, summer day/night, fall and all-season) all have positive asphalt pavement coefficient values, indicating lower fuel consumption on concrete pavement compared to asphalt pavement. In addition, all but one of the composite pavement coefficient values were positive.

3. 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.

4. 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.

5. 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. Figure 4-12.

6. The fuel savings for the full trailer at 60 km/h when comparing concrete to asphalt roads ranged from 0.2 L/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. Figure 4-13.

7. 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. Figure 4-14.

8. 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. Figure 4-15.

9. 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, these analyses showed statistically significant fuel savings when operating on concrete pavement compared to asphalt pavement 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 1.9% to 5.8% in favour of concrete on smooth roads (IRI = 1.0) and were statistically significant.

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

11. The comparison using the two models for Phase III data 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 0.6% and 4.8% and were all statistically significant.

12. The predicted fuel savings on concrete, when compared to asphalt and composite, are very similar when Phase III data 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 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.

# 10 FOLLOW ON WORK

In order to better understand how roads can be built with the aim of reducing greenhouse gas emissions, CSTT recommends the following possible actions for future analysis:

- An in depth study focussing on International Roughness Index (IRI) to determine the effects that road surface roughness can play on fuel consumption;

- An analysis of using concrete pavement on sections of roadway that are primarily exposed to speeds less than 60 km/h, such as intersections or congested urban areas; and

- An expanded scope of work to fully understand other differences between asphalt and concrete pavement surfaces. This would include, but would not be limited to: sound absorption/reflection, noise absorption/reflection, cost of installation, cost of maintenance, propensity to cause/sustain aquaplaning.

# 11 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] Cummins MPG Guide
[4] Cummins Engine Vehicle Evaluation, Vehicle Mission Simulation
[5] MIT, EL 00 – 001

# Appendix A
# Falling Weight Deflectometer Summary Table

| Location | Pavement Type | | **Normalized Deflection (µm)** | | | **Static K-value (Mpa/m)** | | | **Resilient Modulus (Mpa)** | | | **Pavement Modulus ( Mpa)** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Fall 2002 | Spring 2003 | Summer 2003 | Fall 2002 | Spring 2003 | Summer 2003 | Fall 2002 | Spring 2003 | Summer 2003 | Fall 2002 | Spring 2003 | Summer 2003 |
| Highway 417, EB, East of Ottawa | Concrete | Mean | 63 | 79 | 63 | 193 | 153 | 203 | | | | 42,175 | 33,135 | 41,061 |
| | | SD | 9 | 14 | 13 | 67 | 58 | 62 | | | | 9,761 | 10,190 | 11,891 |
| Highway 417, EB, West of Ottawa | Asphalt | Mean | 268 | 240 | 190 | | | | 64 | 81 | 110 | 619 | 650 | 811 |
| | | SD | 60 | 40 | 36 | | | | 15 | 13 | 21 | 144 | 125 | 161 |
| Highway 115, EB, West of Peterborough | Concrete | Mean | 78 | 69 | 65 | 101 | 112 | 121 | | | | 57,655 | 54,091 | 23,798 |
| | | SD | 26 | 10 | 10 | 26 | 22 | 23 | | | | 29,953 | 14,822 | 15,506 |
| Highway 115, WB, West of Peterborough | Asphalt | Mean | 231 | 214 | 149 | | | | 44 | 60 | 94 | 1,418 | 1,198 | 1,580 |
| | | SD | 42 | 34 | 19 | | | | 10 | 12 | 18 | 400 | 276 | 293 |
| Highway 401, WB, near Upper Canada Rd. | Composite | Mean | 143 | 141 | 128 | 60 | 103 | 112 | | | | 7,050 | 5,122 | 6,224 |
| | | SD | 35 | 27 | 25 | 33 | 45 | 51 | | | | 2,603 | 1,586 | 1,979 |