# Additional Analysis of the Effect of Pavement Structure on Truck Fuel Consumption

*Final Report*

Prepared for:

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*This report reflects the views of the authors and not necessarily those of the Cement Association of Canada.*

*Metric measures are generally used throughout this report. However, in some figures may indicate imperial measures as they are copied from original materials.*

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## Executive Summary

This report provides the results of additional statistical analysis of fuel consumption data collected on a semi-trailer tank truck operating on a variety of highway pavement structures in the Ottawa and Montreal region in 1999 and 2000. This data set consisted of three sets of data:

1. vehicle data (speed, fuel flow, wind speed, temperature) was collected on a continuous (approximately 0.5 Hz) basis,
2. road roughness data measured independently and provided as an International Road Roughness (IRI) rating,
3. precision roadway elevation survey to provide grade information.

Statistical Analysis

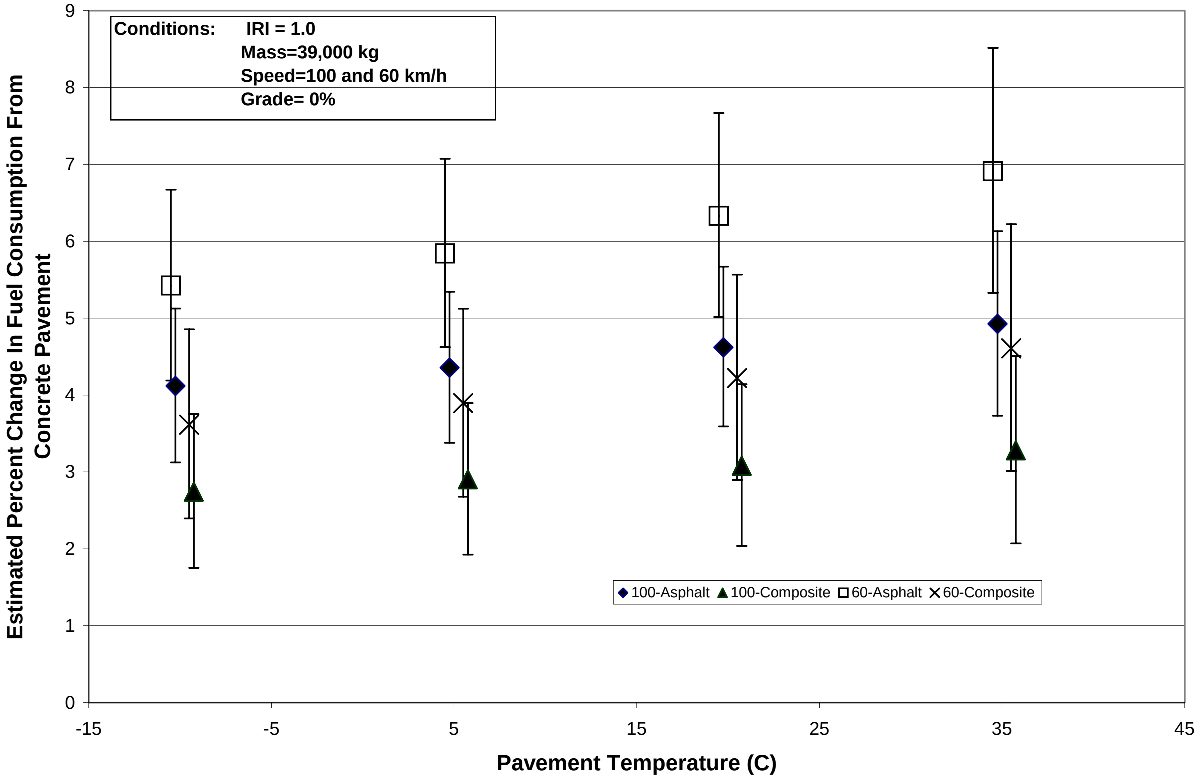
Multivariate linear regression analysis was used to determine the statistically significant factors which explain the variations in fuel consumption.

From the statistical analysis undertaken as part of this study it is concluded that:

1. The databases collected over all seasons were successfully transformed so that the test data and road physical data were merged into a single file with a common time and distance reference with over 64,000 records.
2. The unified data files were then analyzed with a statistical analysis package (Minitab) to determine validity of a number of multiple regression models.
3. The following variables were found to have the highest statistical significance in predicting the fuel consumption of the vehicle - pavement structural type (concrete, asphalt, composite), vehicle load (mass), pavement temperature, road roughness as measured as IRI, road grade, vehicle speed.
4. The variables listed above explained between 60% and 55% of the variation in fuel consumption on roads with IRI up to 2.2, which is quite satisfactory given the large size of the data set.
5. The effect of pavement types on a fully ladened truck on smooth pavements (IRI=1) was found to be sensitive to ambient temperatures. The model indicated that:
    - For all pavement types, fuel consumption at full load and 100 km/h increased as pavement temperatures decreased, on a concrete road the range was from 35.8 L/100km at 35$^{o}$C to 42.8 L/100km at –10 $^{o}$C,
    - Concrete pavements had statistically significant lower fuel consumption than asphalt and composite pavements throughout the temperature range.
    - The Figure below entitled, Estimated Percent Difference In Fuel Consumption from Concrete Pavements, shows the average change in fuel consumption from concrete

pavement at 100 km/h ranges from 4.1 to 4.9 percent for asphalt and 2.7 to 3.2 percent for the composite pavement.

- At 60 km/h, the ranges are 5.4 to 6.9 percent for asphalt and 3.6 to 4.6 percent for the composite pavement.
- The overlapping of the confidence bounds for the asphalt and composite pavement estimated fuel consumption percentage difference values, shown in the figure below, indicate that the differences between asphalt and composite pavements are not statistically significant at the 95% confidence interval.



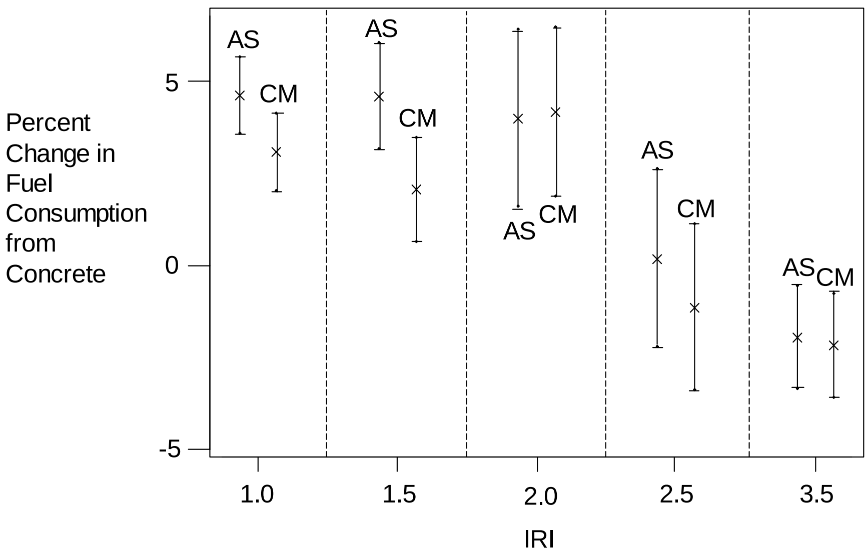

Note: Average values bounded by 95% confidence limits.

Estimated Percent Difference In Fuel Consumption From Concrete Pavements

6. The effect of pavement roughness was assessed at five ranges of IRI values (see Figure below) and it was determined that the percentage change in the fuel consumption between concrete and asphalt and between concrete and composite was insensitive to changes in IRI for pavements with IRI values up to 2.2. Above a roughness of 2.2, the differences between the pavement's fuel consumption was estimated by the model to decrease to 0.2% and –1.1% at an IRI of 2.5, and to –2.0% and –2.2% at an IRI of 3.5, for asphalt and composite pavements, respectively. However, the validity of the models in these higher roughness ranges has high uncertainty for two reasons:

    1) the regression equations are statistically weak (high *p* and low *t* statistics for the equation) for IRI's from 2.2 to 3.0;

2) there is a high probability that the fuel consumption rates on the rough concrete sections (i.e., IRI greater than 3.0) were affected by vehicle momentum effects caused by the greater amount of grade changes in these sections of pavement structure.




Notes: Average values marked as X with 95% confidence limits
Estimated at 20C, a vehicle speed of 100 km/hr, a vehicle load of 39,000 kg, and a grade of 0.
AS=asphalt CM=composite
The statistical quantity of the models for IRI greater than 2.2 are low and these values are only included to illustrate a possible trend.

Estimated Percent Difference From Concrete Pavements At 100 km/h And A Variety of IRI Ranges

## Power Analysis

Additional to the statistical analysis, a vehicle power model was developed to estimate the effect of changes in the rolling resistance coefficient on vehicle fuel consumption at a variety of operating conditions.

The test data was used to calibrate a vehicle power model by estimating the aerodynamic drag and rolling resistance coefficients for the test vehicle. The power model then calculated the effect of this magnitude change in rolling resistance on the vehicle's fuel consumption rate. From the coastdown data obtained in Phase 2, it was estimated that up to a 25% increase in rolling resistance could have occurred between the asphalt and composite types. Using this range of change, the model estimated a maximum percentage change for the fully load configuration of 10.5% at road speeds of between 20 and 50 km/h. At highway speeds, this model predicts a 5 to 6 percent change in fuel consumption with a 25% increase in rolling resistance between concrete and asphalt.

A fuel consumption model from Cummins Engine Co. was used to test the effect of rolling resistance changes on a truck configured as the vehicle used in the Phase 2 test program. By substituting different tire tread design types it was possible to effect a change of the order of 25% in rolling resistance. This model estimated that this magnitude of change in rolling resistance would cause a 13.7 percent increase in fuel consumption (concrete to asphalt) for a fully loaded truck at 100 km/h and 16.8 percent at 75 km/h. For an urban delivery route simulation, the difference was 9.1 percent. In all cases, absolute differences in the fuel consumption rates on concrete compared to asphalt were nominally 4 L/100 km for the fully loaded vehicle.

The vehicle power demand modelling approach can provide reasonable estimates of the fuel consumption changes resulting from pavement rolling resistance changes. However, for greater accuracy more direct measurement of the changes in the coefficient due to pavement, load and temperature changes are required. These values were not directly measured in the testing methodology used in the Phase 2 program.

Experimental Design Recommendations

The following recommendations regarding the collection of additional data are made.

1. The analysis of the test data successfully validated the presence of a statistically significant relationship between pavement structure and fuel consumption for a semi-trailer tank truck operating at steady state conditions at highway speeds. The analysis also proved the usefulness of the application of linear multivariate regression techniques to this type of data set. Any additional data collected should be analyzed in a similar analytical framework using the same techniques.

2. As the effect of increasing road roughness is to increase the variability of the vehicle's fuel consumption rate, it thus decreases the magnitude and statistical reliability of the measured differences due to pavement structure. In order to maximize the accuracy of the measured differences, it is recommended that the range of pavement roughness conditions be constrained to relatively smooth pavements (i.e., IRI less that 2.2).

3. If further understanding and quantification of the effect of road roughness is desired, this work should be undertaken as a separate research program;

4. The type of vehicle and test conditions used in the Phase 2 test program represent a fairly limited range of truck operations. Further, as the performance of a tank trailer has been extensively assessed with the current data set, then it is recommended that any additional data collection should concentrate on expanding the range of the test variables. In particular, the following variables could be modified:

    - Vehicle configuration – test using a van body trailer which represents the majority of heavy trucks on inter-city highways. The test load for this type of vehicle would need to be mechanically loaded – or unloaded - but this would have a positive effect of eliminating the need for local weigh scales for load mass measurement.

    - Expand the maximum test speed to 110 to replicate actual truck in-use cruise speeds. Noted that as this speed is over the posted maximum Provincial agency approval would be needed to undertake the test.

- The mid point speed should be increased from 75 to 80 km/h test condition to correspond to typical posted speeds on urban arterial and undivided inter-city roads.

- The 60 km/h speed should be maintained for comparability and to maximize the variable range.

5. The number of test weight conditions could be reduced if simplifying assumptions about model linearity are used. Loads could be restricted to full and empty given the linearity of relationship between mass and rolling resistance.

6. Ideally all the data on road structure, roughness, grade and vehicle data would be collected simultaneously into a single data file. However, due to the irregular sampling period of the vehicle data system (a function of the Cummins engine control system) such a simultaneous data collect system is not possible. Therefore, at least two data files need to collected and merged through post analysis. Further, in researching the possibility of test vehicle-based collection of the IRI and grade information, it appears that while technically possible, it is financially impractical. Thus, it is recommended that the same data collect system as used in Phase 2 be used for any addition testing. This means that the vehicle (engine, wind, and road temperature), pavement roughness and grade will be collected independent of each other. It is thus very important the truck's physical location on the test section is accurately measured. This was a problem especially on Quebec test sections in Phase 2 as they do not employ road distance markers. This can be solved with the use of temporary distance markers on the roadside. It may also be possible to use relatively low cost on-board GPS equipment to estimate road location to within a few metres resolution.

7. If improved data for input into vehicle power-based models is desired, then direct measurement of the rolling resistance coefficients on the various pavement test sites is required. This is problematic as there are only two ways of collecting the data:

   - Coast down tests which require the closure of stretches of roadway as the speeds are well below posted minimums;

   - Use of a towed rolling resistance dynamometer which, while technically feasible, is not currently in existence. A unit was fabricated and tested in the early 1980's by Transport Canada but was abandoned due to lack of funding, high costs and very sensitive and unreliable instrumentation. Advances in computers and instrumentation may make the construction of a rolling resistance dynamometer more cost-effective and reliable now but its development would involve substantial non-recurring engineering design costs which could only be justified if there was an on-going pavement research program.

8. The statistical analyses undertaken in this study incorporates what the analysis team believes to be the most cost-effective set of analyses of the Phase 2 data set. We see little additional benefit from further analysis of this data. However, this study only used the test data for the semi-trailer configuration. There was additional data collected in summer conditions for a straight tanker and a B-train tanker. These data sets could be analyzed to estimate the same type of regression models and in so doing possibly providing replication and/or expansion of the findings for the semi-trailer.

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# 1. Introduction

## 1.1 Scope of Work

This study's objective was to undertake some re-analysis of effect of pavement structure on heavy truck fuel consumption. The data used in the analysis was that collected in a prior study entitled "Effect of Pavement Surface Type and Fuel Consumption Phase 2: Seasonal Tests" [1]. This report provides the results of additional statistical analysis of fuel consumption data collected on a semi-trailer tank truck operating on a variety of highway pavement structures in the Ottawa and Montreal region in 2000. This data set consisted of three sets of data

1. vehicle data (speed, fuel flow, wind speed, temperature) was collected on a continuous (approximately 0.5 Hz) basis,

2. road roughness data measured independently and provided as an International Road Roughness (IRI) rating,

3. precision roadway elevation survey to provide grade information.

The study analysis was segmented into two distinct areas of effort.

1. the application of multiple regression analysis techniques on the data set for the semi-trailer tanker to identify statistical relationships affecting fuel consumption of the tested vehicle.
2. the use of vehicle road power models to estimate the fuel consequences of changes in vehicle rolling resistance coefficients.

Finally, some opinions on modifications to the design of further field data collection initiatives are provided.

1 National Research Council of Canada report CSTT-HWV-CTR-041, August 2000

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# 2 Multivariate Analysis

## 2.1 Equational Form

Multiple regression was used to investigate the effect of pavement structure on fuel economy. Initially, models were considered where 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 of structure. Vehicle speed was also reflected by two indicator variables, with 60 km/hr set as the base category. This first set of models was fit to data over all seasons, sites, loads, and speeds. For all model fits, no serious difficulties were encountered when assessing assumptions in order to validate the use of the procedures that were employed.

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 this portion of the analysis was

$$Y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \beta_3 X_{i3} + \beta_4 X_{i4} + \beta_5 X_{i5} + \beta_6 X_{i6} + \beta_7 X_{i7} + \beta_8 X_{i8} + \varepsilon_i \qquad (2.1)$$

where

$Y_i$ = Fuel economy associated with the *i*-th observation (*FUEL*),

$X_{i1}$ = 1 if the *i*-th observation is measured on asphalt pavement, and 0 otherwise (*PVASH*),

$X_{i2}$ = 1 if the *i*-th observation is measured on composite pavement, and 0 otherwise (*PVCOMP*),

$X_{i3}$ = Load associated with the *i*-th observation (*LOAD*),

$X_{i4}$ = Pavement temperature associated with the *i*-th observation (*PAVETEMP*),

$X_{i5}$ = IRI associated with the *i*-th observation (*IRI*),

$X_{i6}$ = Road grade associated with the *i*-th observation (*GRADE*),

$X_{i7}$ = 1 if the vehicle speed on the *i*-th observation is 75 km/hr, and 0 otherwise (*SPEED75*), and

$X_{i8}$ = 1 if the vehicle speed on the *i*-th observation is 100 km/hr, and 0 otherwise (*SPEED100*).

The quantity $\varepsilon_i$ reflects the error term associated with the *i*-th observation, which is assumed to be normally distributed with a mean of zero and an unknown variance.

## 2.2 Regression Results

### 2.2.1 All Data

Fitting this model to the data over all seasons, sites, loads, and speeds (64,320 observations in total) yields the results in Table 2-1. Given the number of observations, the coefficient of determination, $R^2$, of 0.541 obtained for this model suggests a fit that is more than satisfactory. An entry in the column labelled "Estimate" provides the expected change in fuel economy in litres/100 km for a one unit increase the associated variable, given that all other variables remain constant. For example, fuel economy is expected to decrease by 0.146 litres/100 km for every $1^{o}$C increase in pavement temperature, given that pavement structure, load, IRI, grade, and vehicle speed remain constant.

Table 2-1 Multiple Regression Results For All Data

| Variable | Estimate | Standard Error | *t*-Ratio | P-value |
|---|---|---|---|---|
| *CONSTANT* | 19.760 | 0.0947 | 209.09 | 0.000 |
| *PVASH* | 0.4682 | 0.06011 | 7.79 | 0.000 |
| *PVCOMP* | -0.02065 | 0.06259 | -0.33 | 0.741 |
| *LOAD* | 0.00030626 | 0.00000244 | 125.37 | 0.000 |
| *PAVETEMP* | -0.146088 | 0.001192 | -122.51 | 0.000 |
| *IRI* | 0.34014 | 0.01636 | 20.79 | 0.000 |
| *GRADE* | 766.394 | 8.060 | 95.08 | 0.000 |
| *SPEED75* | 4.01415 | 0.05018 | 79.99 | 0.000 |
| *SPEED100* | 10.5479 | 0.0548 | 192.49 | 0.000 |

(based on 64,320 observations)

Excluding the two indicator variables for pavement structure, the *t*-ratios associated with the other covariates range in absolute value from 20.79 to 192.49 and their P-values are all zero, suggesting that each has a statistically significant effect on fuel economy. The *t*-ratios associated with the two indicator variables for pavement structure are noticeably smaller. In fact, the ratio linked to the variable *PVCOMP* is less than one and not statistically significant according to the P-value. This would suggest that a difference is not expected in fuel economy on composite and concrete surfaces. In addition, although the results indicate that fuel consumption is expected to be higher on an asphalt surface as compared to a concrete one (all other variables remaining constant), the *t*-ratio of 7.79 associated with *PVASH* illustrates that this effect on fuel economy is not as strong as those of the other variables in the model.

### 2.2.2 IRI Segmentation

Upon further investigation, it was discovered that the IRI values over the observations used to fit the model ranged widely from 0 to slightly above 8. Under the speculation that the effect of varying the pavement structure on fuel economy might be masked on rough roads, it was decided to repeat the above analysis of fitting model (2.1) to five subsets of the overall data set that were distinguished by IRI values. Specifically, these five subsets of data were defined as follows:

Subset 1: Observations over all seasons, sites, loads, and speeds with IRI values of 0 to less than 1.2.

Subset 2: As Subset 1, except that the IRI values range from 1.2 inclusive to less than 1.6.

Subset 3: As Subset 1, except that the IRI values range from 1.6 inclusive to less than 2.2

Subset 4: As Subset 1, except that the IRI values range from 2.2 inclusive to less than 3.0.

Subset 5: As Subset 1, except that the IRI values are 3.0 or more.

It was also noted that the grade variations for the rough concrete sections were substantially higher than for the other test sections as can be seen in Table 2-2. These high grade variations have a substantial effect on the basic underlying assumption that the vehicle is not being affected by inertial effects caused by grade change (acceleration down hill or deceleration uphill). The effect of these momentum changes is expected to increase the variability of the fuel consumption values on the rough concrete sections and thus increase the statistical uncertainty of the comparisons. Thus, the high IRI equations should be viewed as much weaker than for other smoother surfaces – they are included in this report for completeness of the data presentation.

Table 2-2 Comparison of Grade Characteristics of Test Sections

| Test Site | Lane Direction | Pavement | Mean | Standard Deviation | Range | Minimum | Maximum |
|---|---|---|---|---|---|---|---|
| Casselman 417 | East | Asphalt Rough | 0.01% | 0.07% | 0.30% | -0.17% | 0.12% |
| | | Asphalt Smooth | 0.01% | 0.09% | 0.47% | -0.28% | 0.18% |
| | West | Asphalt Rough | 0.00% | 0.06% | 0.18% | -0.08% | 0.10% |
| | | Asphalt Smooth | -0.02% | 0.10% | 0.51% | -0.18% | 0.33% |
| Laval 440/25 | East | Concrete Rough | -0.03% | 0.48% | 2.28% | -1.44% | 0.84% |
| | | Concrete Smooth | -0.19% | 0.37% | 1.82% | -1.41% | 0.41% |
| | | Asphalt | 0.23% | 0.20% | 0.90% | -0.06% | 0.84% |
| | West | Concrete Rough | -0.06% | 0.62% | 2.40% | -0.96% | 1.44% |
| | | Concrete Smooth | 0.22% | 0.41% | 1.70% | -0.49% | 1.20% |
| | | Asphalt | -0.71% | 0.82% | 2.73% | -2.63% | 0.09% |
| Lancaster 401 | East | Composite Rough | -0.12% | 0.33% | 1.88% | -1.53% | 0.36% |
| | | Composite Smooth | 0.00% | 0.09% | 0.44% | -0.24% | 0.20% |
| | West | Composite Rough | 0.06% | 0.17% | 0.82% | -0.37% | 0.45% |
| | | Composite Smooth | 0.00% | 0.09% | 0.47% | -0.23% | 0.24% |
| Vaudreuil 40 | East | Concrete | -0.12% | 0.26% | 1.04% | -0.75% | 0.29% |
| | | Asphalt | -0.03% | 0.09% | 0.68% | -0.61% | 0.08% |
| | West | Concrete | 0.07% | 0.28% | 1.16% | -0.57% | 0.59% |
| | | Asphalt | 0.02% | 0.06% | 0.30% | -0.11% | 0.18% |

The five panels of Table 2-3, labelled (a) through (e), illustrate the results of the regression estimates.  No serious violations in assumptions necessary to validate the appropriateness of these findings were encountered with the exception of the concern about the range of variation on the rough concrete grades mentioned above. The coefficients of determination for the five analyses range from approximately 0.5 to 0.6, suggesting a satisfactory fit for each model. The findings also confirm the hypothesis that the effect of pavement structure on fuel economy is masked on rough roads. For smooth roads where the IRI values range from 0 to 1.2, the *t*-ratios associated with *PVASH* and *PVCOMP* are 16.46 and 10.63 respectively, suggesting that fuel consumption is expected to be higher on asphalt than on concrete, as well as on composite pavement relative to concrete.

On smooth pavements (IRI<1.2) given that all other variables are fixed, fuel consumption is expected to be 1.76 litres/100 km higher on asphalt than on concrete, and 1.17 litres/100 km higher on composite pavement relative to concrete. Notice that as the IRI values increase and the road surface becomes rougher (see panels (b) through (e) in the table), the pavement effects becomes less noticeable to the point where they are not statistically significant for IRI values between 2.2 and 3.0. In addition, for extremely rough roads with IRI values of 3.0 or more, the effects are oddly reversed as evidenced by the negative values for the appropriate *t*-ratios. This may be the effect of the high grades in the rough concrete sections and caution should be used in interpreting panel (e), since for extremely rough roads, the effect of pavement structure on fuel consumption is confounded by the degree of roughness and grade variations.

Table 2-3 Multiple Regression Results Segmented By IRI Ranges

Coefficients obtained by fitting model (2.1) to the data over all seasons, sites, loads, and speeds for different ranges of IRI.

(a) IRI values of 0 to less than 1.2 (22,678 observations). Note that $R^2 = 0.596$.

| Variable | Estimate | Standard Error | *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 |
| *SPEED75* | 3.87459 | 0.0708 | 54.72 | 0.000 |
| *SPEED100* | 10.2833 | 0.0779 | 131.94 | 0.000 |

(b) IRI values of 1.2 inclusive to less than 1.6 (14,772 observations). Note that $R^2 = 0.547$.

| Variable | Estimate | Standard Error | *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* | 1.125 | 0.3874 | 2.90 | 0.004 |
| *GRADE* | 329.86 | 17.20 | 19.17 | 0.000 |
| *SPEED75* | 4.03412 | 0.09936 | 40.60 | 0.000 |
| *SPEED100* | 10.3752 | 0.1066 | 97.29 | 0.000 |

(c) IRI values of 1.6 to less than 2.2 (6,511 observations). Note that $R^2 = 0.502$

| Variable | Estimate | Standard Error | *t*-Ratio | P-value |
|---|---|---|---|---|
| *CONSTANT* | 20.5944 | 0.8445 | 24.39 | 0.000 |
| *PVASH* | 1.5452 | 0.2058 | 7.51 | 0.000 |
| *PVCOMP* | 1.6117 | 0.2069 | 7.79 | 0.000 |
| *LOAD* | 0.00029884 | 0.00000859 | 34.79 | 0.000 |
| *PAVETEMP* | -0.154790 | 0.004401 | -35.17 | 0.000 |
| *IRI* | -0.4889 | 0.4321 | -1.13 | 0.258 |
| *GRADE* | 494.11 | 25.80 | 19.15 | 0.000 |
| *SPEED75* | 4.1148 | 0.1785 | 23.05 | 0.000 |
| *SPEED100* | 10.5820 | 0.1883 | 56.19 | 0.000 |

(d) IRI values of 2.2 inclusive to less than 3.0 (6,282 observations). Note that $R^2 = 0.510$.

| Variable | Estimate | Standard Error | *t*-Ratio | P-value |
|---|---|---|---|---|
| *CONSTANT* | 18.516 | 1.134 | 16.33 | 0.000 |
| *PVASH* | 0.0737 | 0.2511 | 0.29 | 0.769 |
| *PVCOMP* | -0.4689 | 0.2126 | -2.21 | 0.027 |
| *LOAD* | 0.00031864 | 0.00001044 | 30.51 | 0.000 |
| *PAVETEMP* | -0.140232 | 0.005417 | -25.89 | 0.000 |
| *IRI* | 1.0607 | 0.4072 | 2.60 | 0.009 |
| *GRADE* | 1039.55 | 20.61 | 50.44 | 0.000 |
| *SPEED75* | 4.0777 | 0.2169 | 18.80 | 0.000 |
| *SPEED100* | 10.4424 | 0.2248 | 46.45 | 0.000 |

Note: p statistics are high and t statistics low for the PVASH term making this subset model statistically poor

(e) IRI values of 3.0 or more (14,077 observations). Note that $R^2 = 0.549$.

| Variable | Estimate | Standard Error | *t*-Ratio | P-value |
|---|---|---|---|---|
| *CONSTANT* | 20.8563 | 0.3119 | 66.88 | 0.000 |
| *PVASH* | -0.8235 | 0.1469 | -5.61 | 0.000 |
| *PVCOMP* | -0.9193 | 0.1554 | -5.92 | 0.000 |
| *LOAD* | 0.00031629 | 0.00000536 | 59.03 | 0.000 |
| *PAVETEMP* | -0.135686 | 0.002338 | -58.02 | 0.000 |
| *IRI* | 0.16470 | 0.06708 | 2.46 | 0.014 |
| *GRADE* | 975.58 | 18.70 | 52.17 | 0.000 |
| *SPEED75* | 4.1547 | 0.1065 | 39.02 | 0.000 |
| *SPEED100* | 11.0212 | 0.1235 | 89.22 | 0.000 |

Note: The high variability in the grade variation for the concrete section with IRI greater than 3 makes the reliability of the measurements questionable.

### 2.3 Point Estimates

In order to quantify the saving in fuel consumption on concrete relative to asphalt and composite pavements when such surfaces are smooth, point estimates and confidence intervals were determined for expected fuel consumption for each surface at four different pavement temperatures: -10, 5, 20 and 35$^{o}$C. The fit based on panel (a) of Table 2-4 was employed so that an appropriate model for smooth road surfaces could be considered. Calculations were performed using an IRI of 1.0 to reflect a smooth surface and a grade of 0, while vehicle load and speed were set at 39,000 kg and 100 km/hr, respectively. Confidence intervals for expected fuel consumption were obtained at both the 95% and 99% levels.

For each pavement temperature, the point estimates for expected fuel consumption were used to compute a percentage increase in fuel use when driving on asphalt relative to concrete. The

95% confidence intervals for expected fuel consumption on these two surfaces were used to compute an interval for this percentage increase. The lower limit was determined by comparing the lower limit of the 95% confidence interval for economy on asphalt to the upper limit of the analogous interval for concrete. The upper limit was obtained by computing how much higher, in percent, that the upper limit of the 95% confidence interval for consumption on asphalt was than the lower limit of the 95% interval for concrete. Identical calculations were performed using the 99% confidence intervals. This entire procedure was repeated in order to compare composite and concrete surfaces.

The results are presented in panel (a) in Table 2-4. If the 95% confidence intervals for percentage differences are considered, the expected increase in fuel consumption when driving on asphalt instead of concrete under the specified conditions for IRI, grade, vehicle speed and vehicle load ranges from 3.1% to 6.1%. The smallest percent increase occurs at a pavement temperature of $-10^0$C, the largest at the highest temperature of $35^0$C. The analogous expected increase in fuel consumption when driving on a composite surface relative to concrete ranges from 1.8% to 4.5%.

Greater differences in fuel consumption when driving at lower vehicle speeds are expected from mechanical theory. Panel (b) of Table 2-4 presents the results of an identical analysis to that of panel (a), except that all calculations are performed for a vehicle speed of 60 km/hr. If the 95% confidence intervals are again considered, the expected increase in fuel consumption when driving on asphalt instead of concrete ranges from 4.2% to 8.5%. The analogous range for a composite surface relative to concrete is from 2.4% to 6.2%.

Finally, in order to compare the expected change in fuel consumption for different pavement surfaces on rougher roads, the analysis that was performed to produce the results in panel (a) in Table 2-4 was repeated using each of the fits in panels (b), (c), (d) and (e) in Table 2-3. The IRI values used to produce the point and interval estimates were 1.5, 2.0, 2.5 and 3.5 respectively. Panels (a) through (d) of Table 2-5 present the results.

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Table 2-4 Point Estimates Of Fuel Consumption For Smooth Road Surfaces At Four Different Pavement Temperatures

Results are based on the model fit to the data for IRI ranging from 0 to less than 1.2. Increases in fuel consumption for asphalt and composite surfaces relative to concrete.
(a) Calculations are performed at an IRI of 1.0, a load of 39,000 kg, a vehicle speed of **100 km/hr**, and a grade of 0.

| PaveTemp | Surface | Estimate | 95Lower | 95Upper | 99Lower | 99Upper | %Increase | %95Low | %95High | %99Low | %99High |
|---|---|---|---|---|---|---|---|---|---|---|---|
| -10 | Asphalt | 44.577 | 44.391 | 44.764 | 44.332 | 44.823 | 4.118 | 3.125 | 5.127 | 2.813 | 5.446 |
| -10 | Composite | 43.989 | 43.800 | 44.178 | 43.741 | 44.237 | 2.744 | 1.752 | 3.751 | 1.443 | 4.067 |
| -10 | Concrete | 42.814 | 42.581 | 43.046 | 42.508 | 43.119 | --- | --- | --- | --- | --- |
| 5 | Asphalt | 42.244 | 42.081 | 42.407 | 42.030 | 42.459 | 4.355 | 3.380 | 5.343 | 3.078 | 5.656 |
| 5 | Composite | 41.656 | 41.488 | 41.824 | 41.435 | 41.877 | 2.903 | 1.924 | 3.895 | 1.619 | 4.208 |
| 5 | Concrete | 40.481 | 40.256 | 40.705 | 40.186 | 40.775 | --- | --- | --- | --- | --- |
| 20 | Asphalt | 39.911 | 39.755 | 40.068 | 39.705 | 40.117 | 4.621 | 3.591 | 5.670 | 3.267 | 6.001 |
| 20 | Composite | 39.323 | 39.158 | 39.488 | 39.106 | 39.540 | 3.080 | 2.035 | 4.141 | 1.709 | 4.476 |
| 20 | Concrete | 38.148 | 37.918 | 38.377 | 37.846 | 38.449 | --- | --- | --- | --- | --- |
| 35 | Asphalt | 37.578 | 37.408 | 37.748 | 37.355 | 37.801 | 4.925 | 3.730 | 6.132 | 3.362 | 6.515 |
| 35 | Composite | 36.990 | 36.810 | 37.170 | 36.753 | 37.227 | 3.281 | 2.071 | 4.507 | 1.696 | 4.897 |
| 35 | Concrete | 35.815 | 35.567 | 36.063 | 35.489 | 36.140 | --- | --- | --- | --- | --- |

(b) Calculations are performed at an IRI of 1.0, a load of 39,000 kg, a vehicle speed of **60 km/hr**, and a grade of 0.

| PaveTemp | Surface | Estimate | 95Lower | 95Upper | 99Lower | 99Upper | %Increase | %95Low | %95High | %99Low | %99High |
|---|---|---|---|---|---|---|---|---|---|---|---|
| -10 | Asphalt | 34.294 | 34.122 | 34.466 | 34.068 | 34.520 | 5.423 | 4.189 | 6.673 | 3.806 | 7.069 |
| -10 | Composite | 33.706 | 33.534 | 33.878 | 33.479 | 33.932 | 3.615 | 2.394 | 4.853 | 2.011 | 5.245 |
| -10 | Concrete | 32.530 | 32.310 | 32.750 | 32.241 | 32.819 | --- | --- | --- | --- | --- |
| 5 | Asphalt | 31.961 | 31.815 | 32.107 | 31.769 | 32.153 | 5.842 | 4.624 | 7.073 | 4.246 | 7.463 |
| 5 | Composite | 31.373 | 31.223 | 31.522 | 31.176 | 31.569 | 3.894 | 2.677 | 5.122 | 2.300 | 5.511 |
| 5 | Concrete | 30.197 | 29.986 | 30.409 | 29.920 | 30.475 | --- | --- | --- | --- | --- |
| 20 | Asphalt | 29.628 | 29.489 | 29.767 | 29.445 | 29.811 | 6.331 | 5.014 | 7.668 | 4.600 | 8.093 |
| 20 | Composite | 29.040 | 28.894 | 29.186 | 28.848 | 29.231 | 4.221 | 2.895 | 5.567 | 2.480 | 5.990 |
| 20 | Concrete | 27.864 | 27.647 | 28.081 | 27.579 | 28.150 | --- | --- | --- | --- | --- |
| 35 | Asphalt | 27.295 | 27.141 | 27.449 | 27.093 | 27.497 | 6.909 | 5.328 | 8.516 | 4.841 | 9.029 |
| 35 | Composite | 26.707 | 26.544 | 26.869 | 26.493 | 26.921 | 4.606 | 3.011 | 6.223 | 2.519 | 6.745 |
| 35 | Concrete | 25.531 | 25.295 | 25.768 | 25.220 | 25.842 | --- | --- | --- | --- | --- |

Table 2-5 Point Estimates of Fuel Consumption at 100 km/h for Various IRI Values and Pavement Temperatures

(a) Results are based on the model fit to the data for IRI ranging from 1.2 to less than 1.6. Calculations are performed at an IRI of 1.5, a load of 39000, a vehicle speed of 100 km/hr, and a grade of 0.

| PaveTemp | Surface | Estimate | 95Lower | 95Upper | 99Lower | 99Upper | %Increase | %95Low | %95High | %99Low | %99High |
|---|---|---|---|---|---|---|---|---|---|---|---|
| -10 | Asphalt | 45.330 | 45.078 | 45.582 | 44.999 | 45.661 | 4.128 | 2.876 | 5.397 | 2.485 | 5.800 |
| -10 | Composite | 44.338 | 44.072 | 44.604 | 43.989 | 44.688 | 1.849 | 0.580 | 3.135 | 0.184 | 3.545 |
| -10 | Concrete | 43.533 | 43.248 | 43.818 | 43.158 | 43.908 | --- | --- | --- | --- | --- |
| 5 | Asphalt | 43.104 | 42.859 | 43.348 | 42.782 | 43.425 | 4.353 | 3.066 | 5.652 | 2.666 | 6.067 |
| 5 | Composite | 42.112 | 41.861 | 42.362 | 41.782 | 42.441 | 1.951 | 0.666 | 3.249 | 0.266 | 3.664 |
| 5 | Concrete | 41.306 | 41.029 | 41.584 | 40.941 | 41.671 | --- | --- | --- | --- | --- |
| 20 | Asphalt | 40.877 | 40.617 | 41.137 | 40.535 | 41.219 | 4.598 | 3.167 | 6.051 | 2.722 | 6.512 |
| 20 | Composite | 39.885 | 39.628 | 40.142 | 39.547 | 40.223 | 2.060 | 0.655 | 3.485 | 0.218 | 3.938 |
| 20 | Concrete | 39.080 | 38.790 | 39.370 | 38.699 | 39.461 | --- | --- | --- | --- | --- |
| 35 | Asphalt | 38.651 | 38.356 | 38.945 | 38.264 | 39.037 | 4.879 | 3.182 | 6.602 | 2.656 | 7.147 |
| 35 | Composite | 37.659 | 37.375 | 37.943 | 37.285 | 38.032 | 2.187 | 0.543 | 3.8596 | 0.030 | 4.389 |
| 35 | Concrete | 36.853 | 36.533 | 37.173 | 36.433 | 37.274 | --- | --- | --- | --- | --- |

(b) Results are based on the model fit to the data for IRI ranging from 1.6 to less than 2.2. Calculations are performed at an IRI of 2.0, a load of 39000, a vehicle speed of 100 km/hr, and a grade of 0.

| PaveTemp | Surface | Estimate | 95Lower | 95Upper | 99Lower | 99Upper | %Increase | %95Low | %95High | %99Low | %99High |
|---|---|---|---|---|---|---|---|---|---|---|---|
| -10 | Asphalt | 44.946 | 44.536 | 45.357 | 44.407 | 45.486 | 3.560 | 1.486 | 5.683 | 0.842 | 6.358 |
| -10 | Composite | 45.013 | 44.566 | 45.459 | 44.426 | 45.600 | 3.714 | 1.554 | 5.921 | 0.886 | 6.624 |
| -10 | Concrete | 43.401 | 42.918 | 43.884 | 42.767 | 44.036 | --- | --- | --- | --- | --- |
| 5 | Asphalt | 42.624 | 42.217 | 43.032 | 42.089 | 43.160 | 3.761 | 1.637 | 5.933 | 0.981 | 6.626 |
| 5 | Composite | 42.691 | 42.285 | 43.097 | 42.158 | 43.224 | 3.924 | 1.801 | 6.093 | 1.147 | 6.784 |
| 5 | Concrete | 41.079 | 40.622 | 41.537 | 40.478 | 41.680 | --- | --- | --- | --- | --- |
| 20 | Asphalt | 40.303 | 39.859 | 40.746 | 39.720 | 40.886 | 3.989 | 1.616 | 6.414 | 0.884 | 7.191 |
| 20 | Composite | 40.369 | 39.965 | 40.773 | 39.838 | 40.901 | 4.159 | 1.887 | 6.485 | 1.184 | 7.231 |
| 20 | Concrete | 38.757 | 38.290 | 39.225 | 38.143 | 39.372 | --- | --- | --- | --- | --- |
| 35 | Asphalt | 37.981 | 37.470 | 38.492 | 37.309 | 38.653 | 4.240 | 1.416 | 7.148 | 0.542 | 8.081 |
| 35 | Composite | 38.047 | 37.605 | 38.490 | 37.466 | 38.629 | 4.421 | 1.781 | 7.143 | 0.965 | 8.014 |
| 35 | Concrete | 36.436 | 35.924 | 36.947 | 35.763 | 37.108 | --- | --- | --- | --- | --- |

(c) Results are based on the model fit to the data for IRI ranging from 2.2 to less than 3.0. Calculations are performed at an IRI of 2.5, a load of 39000, a vehicle speed of 100 km/hr, and a grade of 0.

| PaveTemp | Surface | Estimate | 95Lower | 95Upper | 99Lower | 99Upper | %Increase | %95Low | %95High | %99Low | %99High |
|---|---|---|---|---|---|---|---|---|---|---|---|
| -10 | Asphalt | 45.514 | 44.993 | 46.034 | 44.829 | 46.198 | 0.163 | -2.138 | 2.516 | -2.852 | 3.271 |
| -10 | Composite | 44.971 | 44.448 | 45.494 | 44.283 | 45.658 | -1.032 | -3.323 | 1.314 | -4.035 | 2.063 |
| -10 | Concrete | 45.440 | 44.904 | 45.976 | 44.735 | 46.145 | --- | --- | --- | --- | --- |
| 5 | Asphalt | 43.410 | 42.914 | 43.906 | 42.759 | 44.062 | 0.171 | -2.061 | 2.452 | -2.752 | 3.180 |
| 5 | Composite | 42.867 | 42.402 | 43.333 | 42.256 | 43.479 | -1.082 | -3.229 | 1.115 | -3.896 | 1.815 |
| 5 | Concrete | 43.336 | 42.855 | 43.817 | 42.704 | 43.969 | --- | --- | --- | --- | --- |
| 20 | Asphalt | 41.307 | 40.786 | 41.827 | 40.622 | 41.991 | 0.179 | -2.213 | 2.625 | -2.953 | 3.406 |
| 20 | Composite | 40.764 | 40.306 | 41.222 | 40.161 | 41.366 | -1.137 | -3.364 | 1.141 | -4.054 | 1.867 |
| 20 | Concrete | 41.233 | 40.757 | 41.709 | 40.608 | 41.858 | --- | --- | --- | --- | --- |
| 35 | Asphalt | 39.203 | 38.614 | 39.793 | 38.428 | 39.978 | 0.189 | -2.615 | 3.069 | -3.484 | 3.990 |
| 35 | Composite | 38.660 | 38.156 | 39.165 | 37.997 | 39.323 | -1.199 | -3.770 | 1.443 | -4.566 | 2.286 |
| 35 | Concrete | 39.129 | 38.608 | 39.651 | 38.444 | 39.815 | --- | --- | --- | --- | --- |

Note: p statistics are high and t statistics low for the PVASH term making this subset model statistically poor

(d) Results are based on the model fit to the data for IRI of 3.0 or more. Calculations are performed at an IRI of 3.5, a load of 39000, a vehicle speed of 100 km/hr, and a grade of 0.

| PaveTemp | Surface | Estimate | 95Lower | 95Upper | 99Lower | 99Upper | %Increase | %95Low | %95High | %99Low | %99High |
|---|---|---|---|---|---|---|---|---|---|---|---|
| -10 | Asphalt | 45.323 | 44.994 | 45.652 | 44.890 | 45.756 | -1.783 | -3.172 | -0.378 | -3.605 | 0.070 |
| -10 | Composite | 45.227 | 44.909 | 45.545 | 44.809 | 45.645 | -1.992 | -3.355 | -0.611 | -3.779 | -0.173 |
| -10 | Concrete | 46.146 | 45.825 | 46.468 | 45.724 | 46.569 | --- | --- | --- | --- | --- |
| 5 | Asphalt | 43.288 | 42.984 | 43.591 | 42.889 | 43.686 | -1.866 | -3.224 | -0.491 | -3.646 | -0.055 |
| 5 | Composite | 43.192 | 42.893 | 43.491 | 42.799 | 43.585 | -2.083 | -3.429 | -0.719 | -3.848 | -0.286 |
| 5 | Concrete | 44.111 | 43.806 | 44.416 | 43.710 | 44.512 | --- | --- | --- | --- | --- |
| 20 | Asphalt | 41.252 | 40.960 | 41.544 | 40.868 | 41.636 | -1.958 | -3.351 | -0.546 | -3.783 | -0.096 |
| 20 | Composite | 41.156 | 40.861 | 41.452 | 40.768 | 41.545 | -2.187 | -3.584 | -0.766 | -4.019 | -0.314 |
| 20 | Concrete | 42.076 | 41.772 | 42.380 | 41.676 | 42.475 | --- | --- | --- | --- | --- |
| 35 | Asphalt | 39.217 | 38.920 | 39.513 | 38.827 | 39.607 | -2.055 | -3.563 | -0.529 | -4.031 | -0.040 |
| 35 | Composite | 39.121 | 38.814 | 39.428 | 38.717 | 39.525 | -2.295 | -3.826 | -0.743 | -4.303 | -0.247 |
| 35 | Concrete | 40.040 | 39.723 | 40.358 | 39.623 | 40.458 | --- | --- | --- | --- | --- |

Note: The high variability in the grade variations for the concrete section with IRI greater than 3 makes the reliability of the measurements questionable.

A number of the model estimates in Table 2-4 and Table 2-5 have been plotted in the figures below. In Figure 2-1, the fuel consumption estimates at 100 and 60 km/h at four pavement temperatures on smooth pavements (IRI values from 0.0 to less than 1.2) are shown. In Figure 2-2, the percent changes in fuel consumption from concrete to asphalt and composite pavements at the four pavement temperatures are provided. Calculations are based on estimates and 95% confidence intervals for expected fuel consumption that were determined for a vehicle speeds of 100 and 60 km/hr, a vehicle load of 39,000 kg, and a grade of 0.

It can be seen in Figure 2-1 that there is a marked increase in the fuel consumption rates as temperature decreases. The differences between concrete and the other pavement types are statistically significant at the 95$^{th}$ percentile confidence limit.

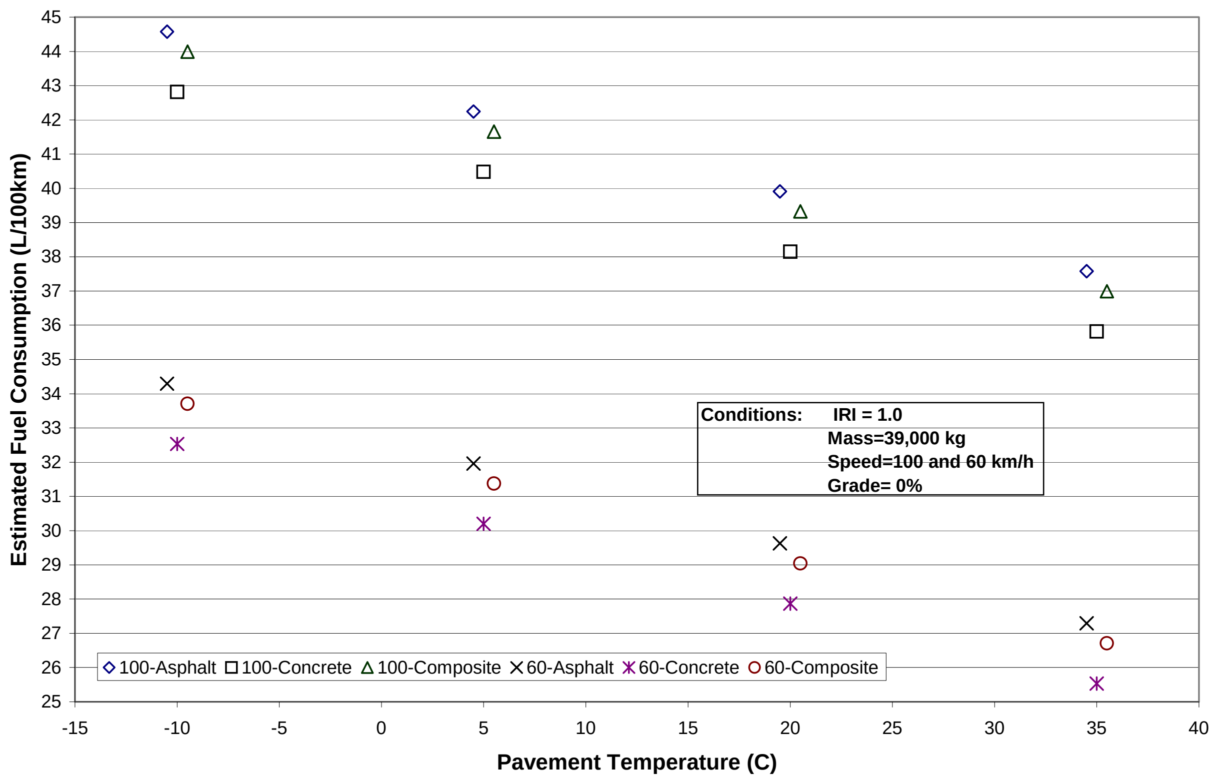
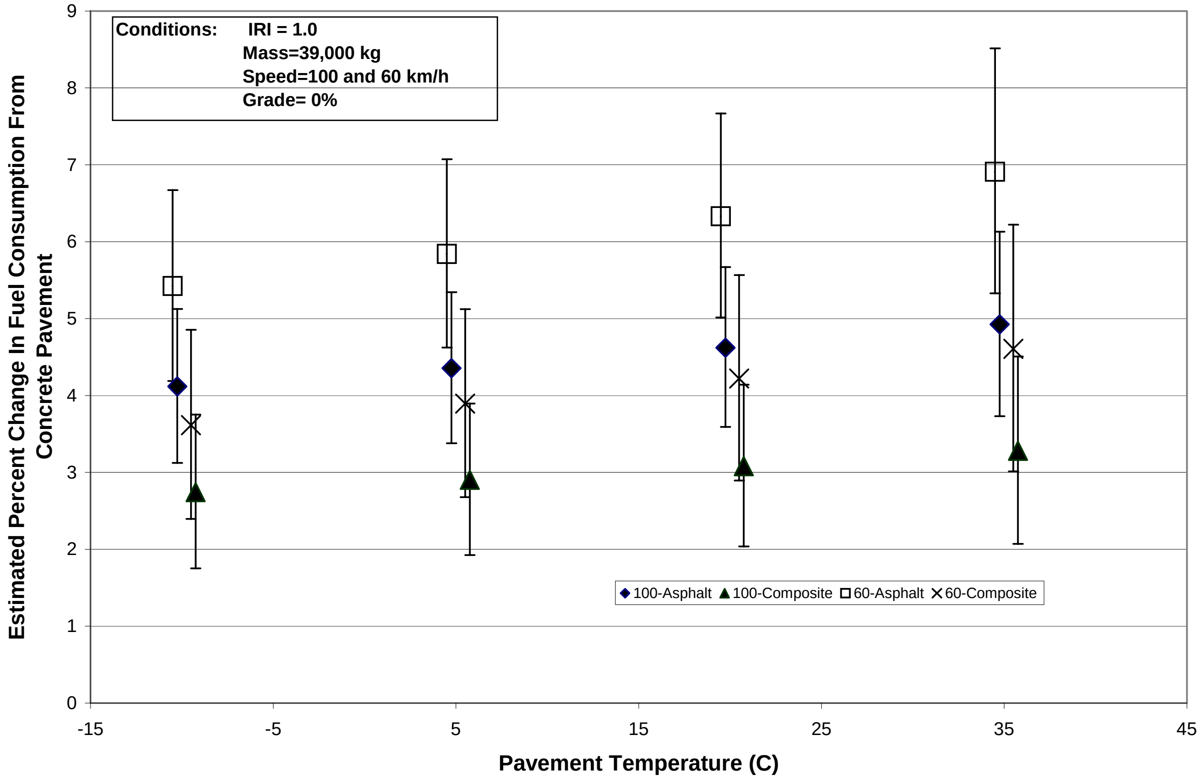



Figure 2-1 Fuel Consumption Estimates On IRI=1 Pavements

Figure 2-2 shows the point and interval estimates for smooth (IRI values from 0.0 to less than 1.2) asphalt and composite roads at 100 and 60 km/h for four pavement temperatures as a percent change in fuel consumption from concrete pavement. Again, calculations are based on estimates and 95% confidence intervals for expected fuel consumption that were determined for a vehicle load of 39,000 kg, and a grade of 0. The data shows that the average change in fuel consumption from concrete pavement at 100 km/h ranges from 4.1 to 4.9 percent for asphalt and 2.7 to 3.2 percent for the composite pavement. At 60 km/h, the ranges are 5.4 to 6.9 percent for asphalt and 3.6 to 4.6 percent for the composite pavement.

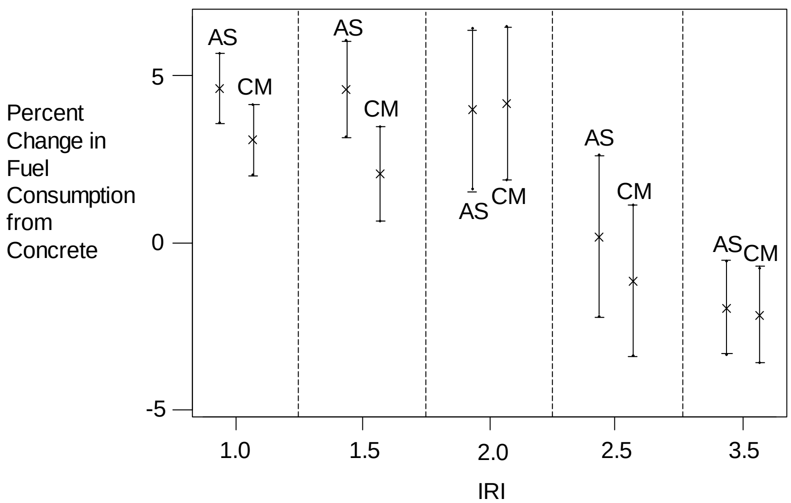



Note: Average values bounded by 95% confidence limits.

Figure 2-2 Estimated Percent Difference In Fuel Consumption At 100 km/h

Note that the percentage differences between the pavements are higher at the lower speed as the drag effects of rolling resistance are a higher percentage of the total road load forces. The overlaps of the confidence bounds indicate that the percentage differences are not statistically different between asphalt and composite pavements – but that there is a statistical difference from concrete pavements. There is also a consistent trend for the percentage differences to increase with temperature but the overlaps of the 95$^{th}$ percentile bounds indicate that the differences are not statistically significant.

The effect of road roughness changes is seen in the data plotted in Figure 2-3 which illustrates the point and interval estimates for the percent change in fuel consumption from concrete to asphalt (AS) and composite (CM) at five different roughness levels for pavement surface. Calculations are based on estimates and 95% confidence intervals for expected fuel consumption that were determined for a pavement temperature of 20$^{o}$C, a vehicle speed of 100 km/hr, a vehicle load of 39,000 kg, and a grade of 0. It can be seen in the Figure that the effect of increasing roughness up to the 2.2 boundary has no statistically significant effect on the percentage differences in the fuel consumption rates. Within this IRI range, both asphalt and composite pavements exhibit an average 3.7 percent increase in fuel consumption over the concrete pavement. The differences from concrete, according to the models, are negated at higher IRI ranges which intuitively seems correct as the increase in the roughness should significantly increase the rolling resistance making the pavement material differences of less consequence. However, because of the weakness of the statistical fit of the IRI 2.2 to 3.0 model and the concerns about data quality in the over 3.0 IRI model, the reliability of this finding in questionable.




Notes: Average values marked as X with 95% confidence limits
Estimated at 20C, a vehicle speed of 100 km/hr, a vehicle load of 39,000 kg, and a grade of 0.
AS=asphalt CM=composite
The statistical quantity of the models for IRI greater than 2.2 are low and these values are only included to illustrate a possible trend.

Figure 2-3 Estimated Percent Difference From Concrete Pavements At 100 km/h And A Variety of IRI Ranges

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# 3 Vehicle Power Model

In conjunction with the statistical analysis, a road load power model of the tanker semi-trailer vehicle used in the Phase 2 test program was developed based on the application of a physical model of resistive forces acting on the truck. This model was then used to estimate the sensitivity of total road power demand and fuel consumption to changes in the rolling resistance values.

## 3.1 Power Model

The power required to move a vehicle is the total of a series of individual power requirements. These are based on standard Newtonian physical relationships such that to maintain a specific speed a vehicle must over come opposing forces of inertia (in the case of grade or acceleration), rolling resistance of the tires on the pavement, and aerodynamic resistance.

### 3.1.1 Coast Down Tests

During the Phase 2 study an incomplete set of coast down tests were completed [2] on the semi-trailer tanker vehicle. These tests involved bring the vehicle up to a target speed at either a “high” speed (~70 - 60 km/h) and a “low” speed (~15 km/h) at which time the vehicle’s clutch is engaged and the engine brought to idle. The vehicle is then allowed to coast down under the influence of the external forces for a period of time. From the time and speed data recorded during the test, estimates of both the aerodynamic and rolling resistance factors can be made. The test is very sensitive to grade changes (assumes equal grades) and to sudden changes in the ambient wind. As the test sites of the tests were only “nominally” flat the test results showed some scatter in the estimated values. Also, as mentioned above, only asphalt and composite pavements were assessed.

The data from the 417 (asphalt) and 401 (composite) sites were processed to determine the estimates of the rolling resistance coefficients as provided in Table 3-1. The calculated rolling resistance coefficients indicate that the asphalt pavement had a higher resistance coefficient than the composite (~20% on the low IRI test sections) on both the low and high IRI sections of the test area. From the analysis in Phase 2, it was seen that the composite pavements were similar to performance to the concrete sections so it is reasonable to expect that the same type of difference would be a first approximation of the concrete’s performance. Thus, a difference range of 20-25% in the rolling resistance coefficient was selected for the analysis of fuel consumption through a vehicle power model.

2 as the vehicle speeds were below the minimum posted speeds, the tests were cancelled after the 417 and 401 data were collected.

Table 3-1 Coefficients from Coast Down Tests

| Roughness | Pavement Type | Rolling Coefficient |
|---|---|---|
| Low IRI | 401 Composite | 0.0042 |
| | 417 Asphalt | 0.0050 |
| High IRI | 401 Composite | 0.0046 |
| | 417 Asphalt | 0.0050 |

### 3.1.2 Power Model Analysis

The mathematical relationships of force to road speed were developed into a spreadsheet model. This model was formulated as

L/100km=(engine_efficiency*drivetrain_efficiency*(mass*gravitation_constant*rolling_coeff*cos(%grade)+ air_density/2*frontal_area*wind_speed^2)+mass*(acceleration+gravitation_constant*sin(%grade )+dummy_variable)*wind_speed*distance)/distance

And used the variable values shown in Table 3-2.

Table 3-2 Vehicle Model Parameters

| Variable | Range of Values |
|---|---|
| vehicle mass | 17100 to 38900 kg |
| aerodynamic drag coefficient | 0.8 |
| frontal area | 7.5m |
| rolling resistance coefficient | 0.004 to 0.005 |
| air temperature (air density) | 23C |
| Grade | 0% |
| vehicle engine efficiency | 40% |
| drivetrain efficiency | 90% |

The model is a relatively simple steady state (constant speed) model but allows manipulation of the variables to calibrate the various coefficients to a subset of actual test. For the base calibration, the summer data for the concrete section of Quebec highway 40 was used. Through iteration of the rolling resistance values, an optimized value was selected that gave the best replication of the test data as shown in Figure 3-1. These results were achieved with a CR = 0.004 which is similar to the coast down data for composite pavement. In the chart can be seen the relatively good fit of the modelled data to the actual the 60 and 100 km/h tests (the 75 km/h test data seem somewhat erroneous).

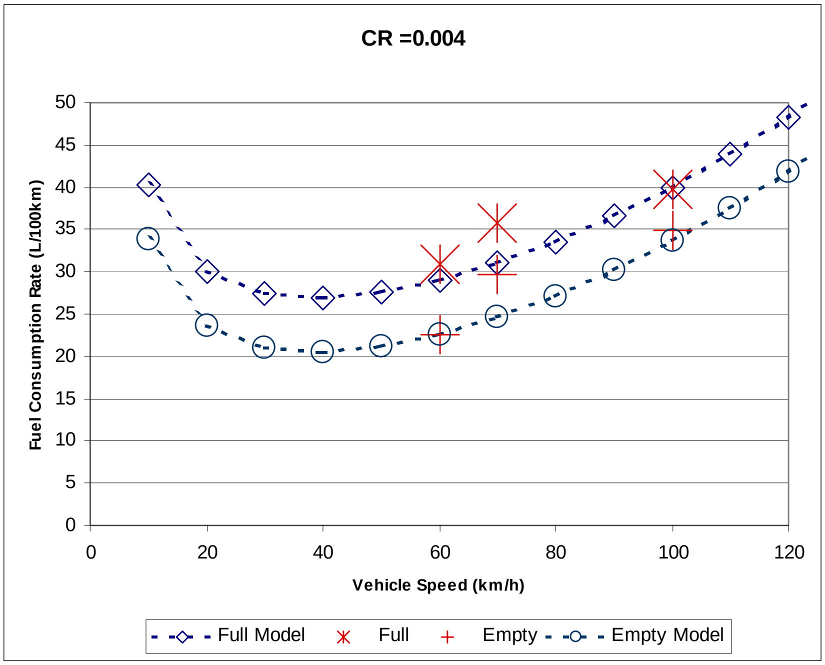


Figure 3-1 Concrete Pavement Vehicle Model

The model then calculated the fuel consumption rates with a 25% increase in the rolling resistance coefficient (0.005). The two outputs are compared in Figure 3-2 and it can be seen that the effect is to offset the fuel use upwards throughout the speed range. When the percentage change is calculated for each speed, as is presented in Figure 3-3, the highest percentage change (10.5% for fully loaded condition) occurs in the speed range of 20 to 50 km/h – where rolling resistance is the large percentage of the total drag on the vehicle.

The percentage change estimates at the higher speeds are in the range measured in the Phase 2 analysis and give some credance to this modeling. The fact that percentage changes are highest at lower road speeds is an important observation as this means that the influence of pavement structure is potentially more important in urban roads. However, this observation must be tempered with the fact that there is a significantly lower percentage of vehicle operations that occur at close to steady speed on urban roads and the energy use for acceleration changes will be substantial and reduce the magnitude of the overall change due to the pavement structure.

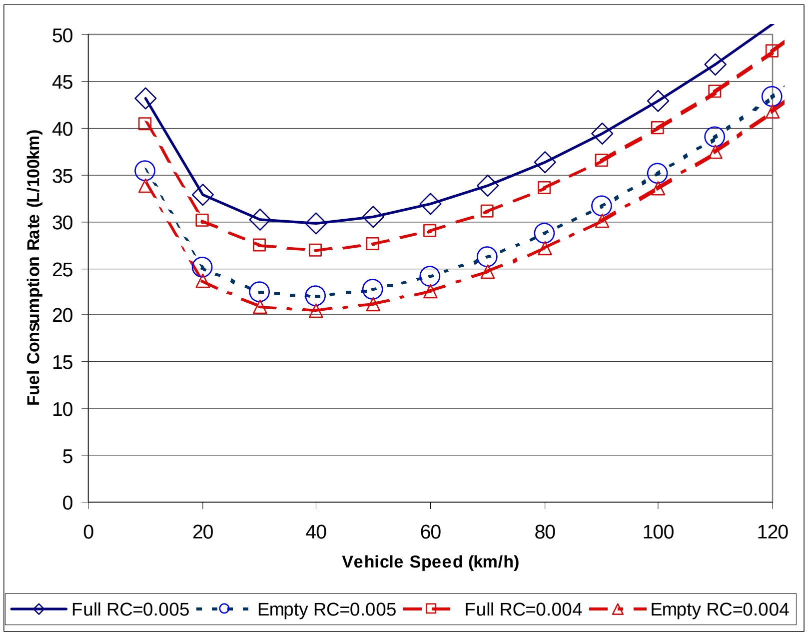


Figure 3-2 Comparison of CR=0.004 and CR=0.005 Model Outputs

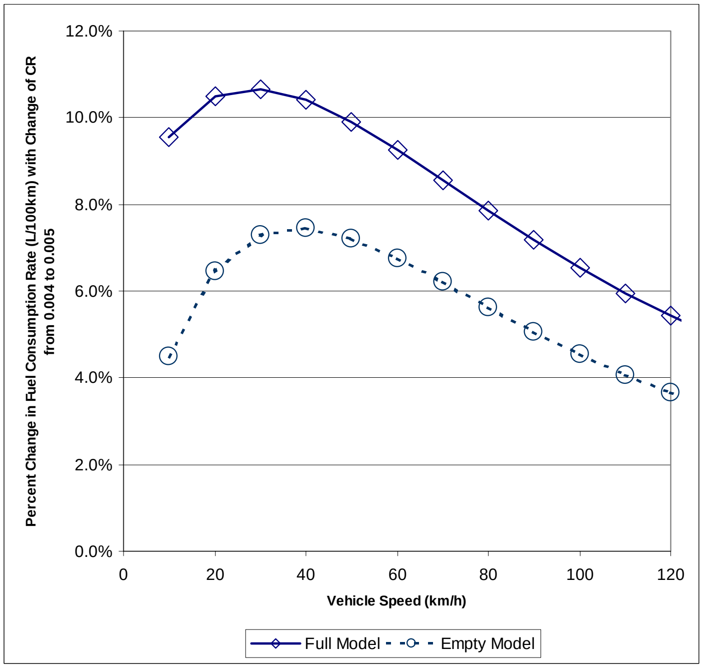


Figure 3-3 Percent Change in Fuel Consumption With Change in Rolling Resistance

### 3.2 Cummins Vehicle Model

Cummins Engine Co. has developed a similar (but much more complex) power based simulation model for their engine products which is called VE/VMS (Vehicle Evaluation/Vehicle Mission Simulation). This model was used to replicate the truck used in the Phase 2 study and to estimate the influence that a change in rolling resistance of the tires would have on fuel consumption. This emulates a pavement change. The tires available for specification in the model include low rolling resistance rib, standard rib, lug, and extra deep lug. In discussions with Cummins [3] it was determined that the rolling resistance changes by approximately 25% between the low rolling resistance tires and the extra lug tires. This is the similar rolling resistance change that measured in the coast down tests provides an estimate of the maximum difference between asphalt and concrete roads (both having low IRI values).

The VE/VMS model provides a variety of output formats for the calculated estimates. Figure 3-4 and Figure 3-5 provide a segmentation of the total road power into miscellaneous (HVAC, electrical, etc.), rolling and aerodynamic power requirements from 0 through 140 km/h. The totals at 100 km/h are shown on each chart. The model calculates a road power increase of 15 kW between the two configurations which represent a 25% increase in the rolling resistance of the vehicle.

Table 3-3 Cummins Tire Rolling Resistance Values

| Type Construction Type | Percent Change In Rolling Resistance From Rib |
|---|---:|
| Low Rolling Resistance Rib | -4% |
| Standard Rib | 0% |
| Lug Pattern | 10% |
| Extra Deep Lug Pattern | 20% |

The model was run for a variety of road speed conditions with empty (17100 kg) and full (38900 kg) vehicle masses. The VE/VMS model also allows the selection of specific route types so an inter-state (1-2% grade) and urban delivery route options were used. Within the inter-state route type, cruise speeds of 100 and 75 km/h were used to replicate the Phase 2 test conditions.

The model’s estimates for fuel consumption rates at each condition are presented in Table 3-4. The fuel consumption differences indicate the asphalt pavement could increase fuel use by up to 13.7% at 100 km/h cruise, 16.8% at 75 cruise (a relatively unlikely condition) and by about 8.5% for urban delivery routes (again a low incidence condition for the semi-trailer configuration).

These estimates of fuel impact represent the probable extreme in effects by assuming a 25% change in the rolling resistance due a pavement structure change. If additional rolling resistance data for a variety of pavement types and roughness conditions can be compiled them more precise assessments can be made.

The analysis however, clearly indicates the pavement rolling resistance plays a large part in total fuel use and also indicates that the savings in energy may be as significant in urban conditions as they are on inter-city high speed roads.

3 Telephone conversation with Clint Morris Cummins VE/VMS support

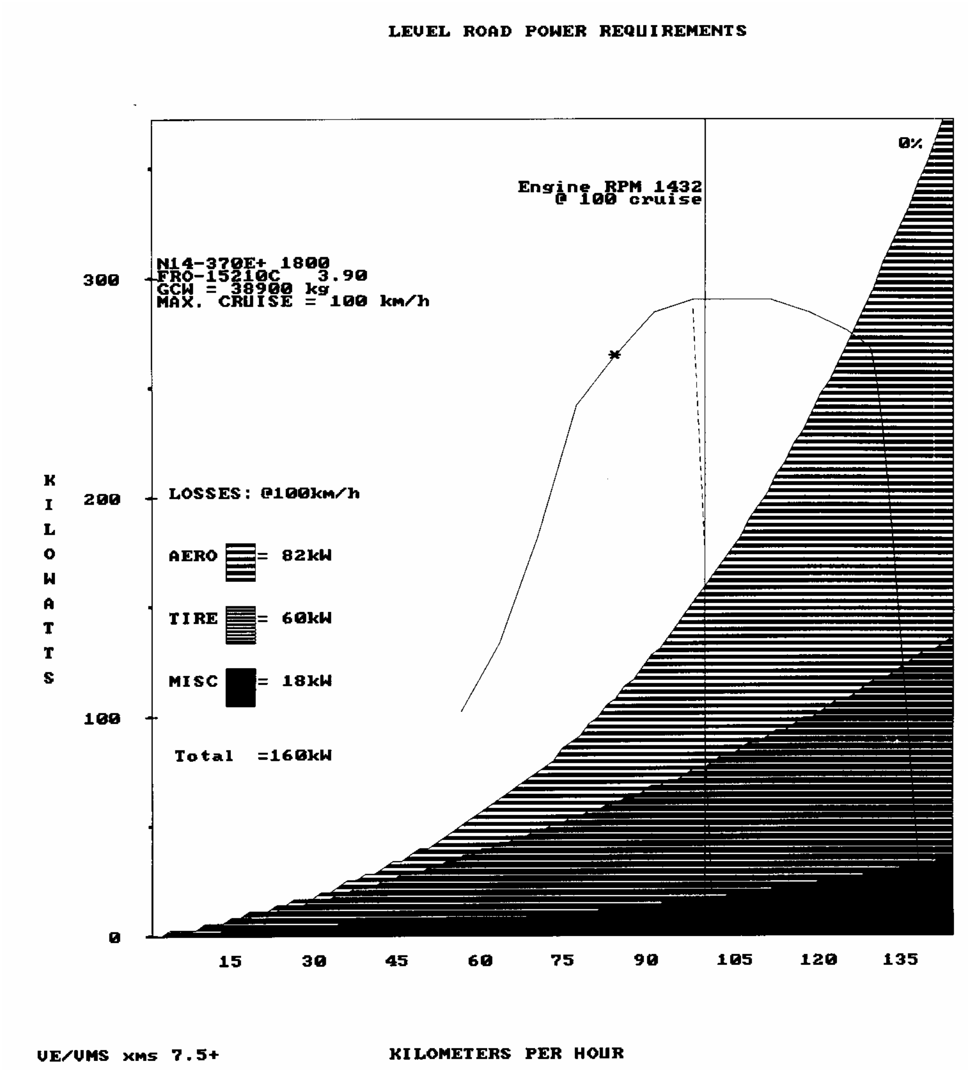


Figure 3-4 Road Power Demand with Low Rolling Resistance Tires

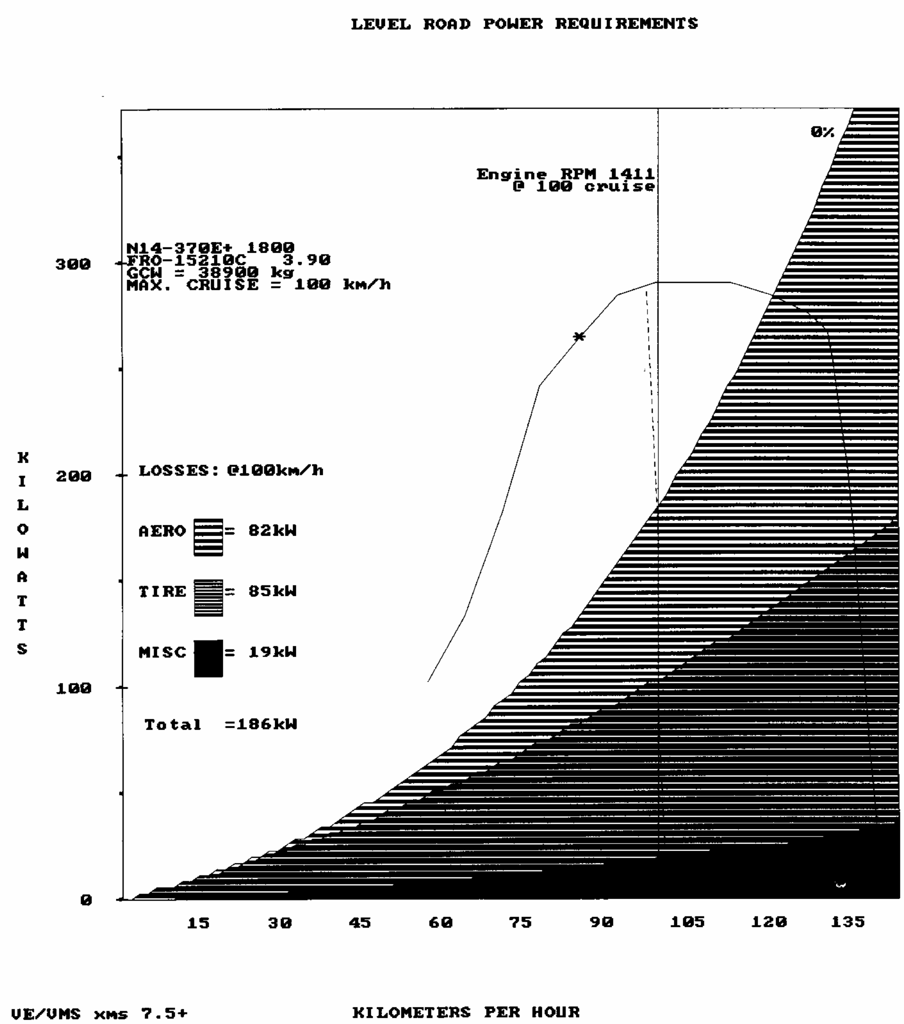


Figure 3-5 Road Power Demand with High Rolling Resistance Tires

Table 3-4 VE/VMS Fuel Consumption Estimates

| Speed | Vehicle Mass (kg) | Average Fuel Consumption (L/100km) | | % Change from LRR |
|---|---|---|---|---|
| | | LRR | LUGX | |
| 100 flat | 38900 | 36.6 | 41.6 | 13.7% |
| | 17100 | 29.5 | 31.6 | 7.1% |
| 75 flat | 38900 | 28.0 | 32.7 | 16.8% |
| | 17100 | 21.3 | 23.3 | 9.4% |
| Urban | 38900 | 46.4 | 50.6 | 9.1% |
| | 17100 | 44.0 | 48.1 | 9.3% |

Legend : LRR – Low Rolling Resistance tires
LugX – Extra Deep Lug pattern tires

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# 4 Conclusions and Recommendations

### 4.1 Conclusions from the Statistical Analysis

From the statistical analysis undertaken as part of this study it is concluded that:

1. The databases collected over all seasons were successfully transformed so that the test data and road physical data were merged into a single file with a common time and distance reference.

2. The unified data files were then analyzed with a statistical analysis package (Minitab) to determine validity of a number of multiple regression models.

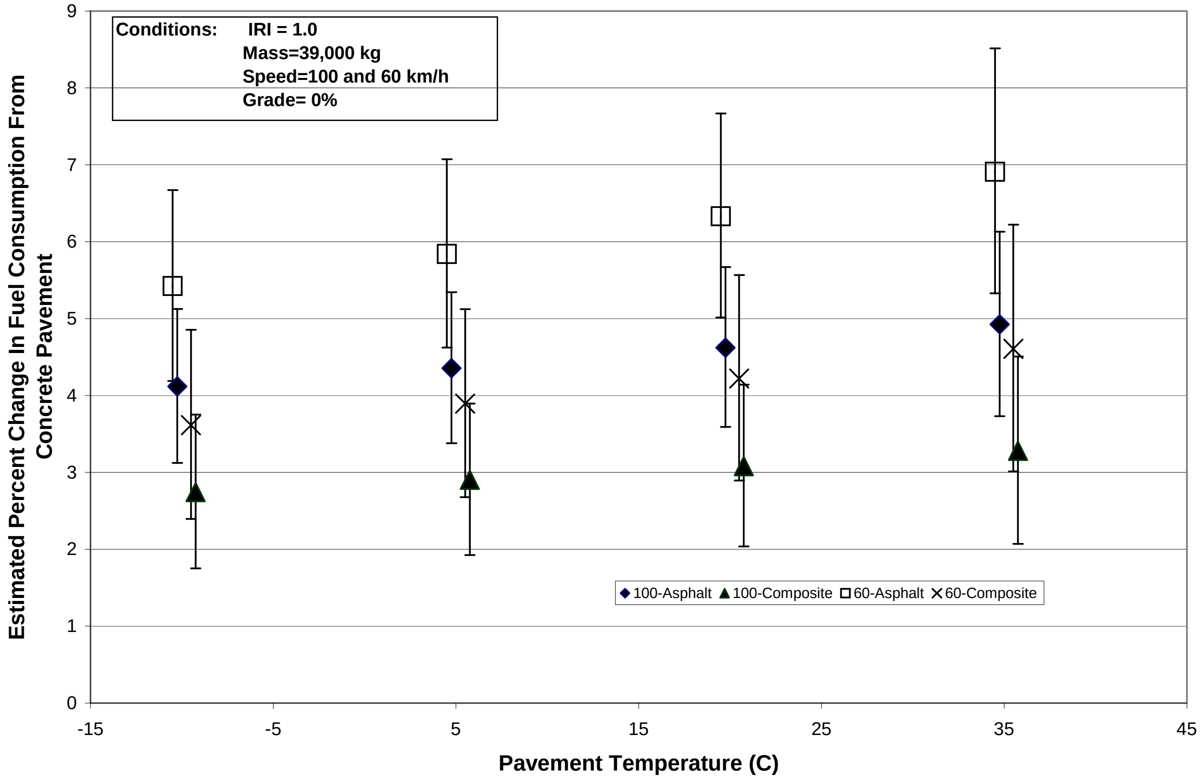
3. The following variables were found to have the highest statistical significance in predicting the fuel consumption of the vehicle:

    - Pavement Structural Type (Concrete, Asphalt, Composite)
    - Vehicle Load (mass)
    - Pavement Temperature
    - Road roughness as measures as IRI
    - Road Grade
    - Vehicle speed

4. The variables listed above explained between 60% and 55% of the variation in fuel consumption on roads with IRI less than 1.2, 1.2 to 1.6 and between 1.6 and 2.2, which is quite satisfactory given the large size of the data set.

5. The effect of pavement types on a fully ladened truck on smooth pavements (IRI=1) was found to be sensitive to ambient temperatures. The model indicated that:

    - For all pavement types, fuel consumption increased as pavement temperatures decreased, on a concrete road the range was from 35.8 L/100km at 35$^{o}$C to 42.8 L/100km at –10$^{o}$C,
    - Concrete pavements had statistically significant lower fuel consumption than asphalt and composite pavements throughout the temperature range.
    - The Figure below entitled, Estimated Percent Difference In Fuel Consumption from Concrete Pavements, shows the average change in fuel consumption from concrete pavement at 100 km/h ranges from 4.1 to 4.9 percent for asphalt and 2.7 to 3.2 percent for the composite pavement.
    - At 60 km/h, the ranges are 5.4 to 6.9 percent for asphalt and 3.6 to 4.6 percent for the composite pavement.
    - The overlapping of the confidence bounds for the asphalt and composite pavement estimated fuel consumption percentage difference values, shown in the figure below, indicate that the differences between asphalt and composite pavements are not statistically significant at the 95% confidence interval.




Note: Average values bounded by 95% confidence limits.

Estimated Percent Difference In Fuel Consumption From Concrete Pavements

6) The effect of pavement roughness was assessed at five ranges of IRI values and it was determined that the percentage change in the fuel consumption between concrete and asphalt and between concrete and composite was insensitive to changes in IRI for pavements with IRI values up to 2.2. Above a roughness of 2.2, the differences between the pavement's fuel consumption was estimated by the model to decrease to 0.2% and –1.1% at an IRI of 2.5, and to –2.0% and –2.2% at an IRI of 3.5, for asphalt and composite pavements, respectively. However, the validity of the models in these higher roughness ranges has high uncertainty for two reasons:

1) the regression equations are statistically weak (high *p* and low *t* statistics for the equation) for IRI's from 2.2 to 3.0;
2) there is a high probability that the fuel consumption rates on the rough concrete sections (i.e., IRI greater than 3.0) were affected by vehicle momentum effects caused by the greater amount of grade changes in these sections of pavement structure.

### 4.2 Conclusions from the Power Model Analysis

From the coast down data obtained in Phase 2, it was estimated that perhaps up to a 25% increase in rolling resistance could have occurred among to three pavement types. The test data was used to calibrate a vehicle power model by estimating the aerodynamic drag and rolling resistance coefficients for the test vehicle. The power model then calculated the effect of this magnitude change in rolling resistance on the vehicle's fuel consumption rate. The estimates indicated a maximum percentage change for the fully load configuration of 10.5% at road speeds of between 20 and 50 km/h. At highway speeds is model predicts a 5 to 6 percent change between concrete and asphalt conditions.

A fuel consumption model from Cummins Engine Co. was used to test the effect of rolling resistance changes on a truck configured as the vehicle used in the Phase 2 test program. By substituting different tire tread design types, it was possible to effect a change of the order of 25% in rolling resistance. This model estimated that this change in rolling resistance would cause a 13.7 percent increase in fuel consumption (concrete to asphalt) for a fully loaded truck at 100 km/h and 16.8 percent at 75 km/h. For an urban delivery route simulation, the difference was 9.1 percent. In all cases, absolute differences were nominally 4 L/100 km for the fully loaded vehicle.

The vehicle power demand modelling approach can provide reasonable estimates of the fuel consumption changes resulting from pavement rolling resistance changes. However, this requires direct measurement of the changes in the coefficient that are likely to be occur due to pavement, load and temperature changes. These values were not directly measured in the testing methodology used in the Phase 2 program.

### 4.3 Experimental Design Recommendations

1. The analysis of the tests data successfully validated the presence of a statistically significant relationship between pavement structure and fuel consumption for a semi-trailer tank truck operating at steady state conditions at highway speeds. The analysis also proved the usefulness of the application of linear multivariate regression techniques to this type of data set. Any additional data collected should be analyzed in a similar analytical framework using the same techniques.

2. As the effect of increasing road roughness is to increase the variability of the vehicle's fuel consumption rate, it thus decreases the magnitude and statistical reliability of the measured differences due to pavement structure. In order to maximize the accuracy of the measured differences, it is recommended that the range of pavement roughness conditions be constrained to relatively smooth pavements (i.e., IRI less that 2.2).

3. If further understanding and quantification of the effect of road roughness is desired, this work should be undertaken as a separate research program;

4. The type of vehicle and test conditions used in the Phase 2 test program represent a fairly limited range of truck operations. Further, as the performance of a tank trailer has been extensively assessed with the current data set, then it is recommended that any additional data collection should concentrate on expanding the range of the test variables. In particular, the following variables could be modified:

    - Vehicle configuration – test using a van body trailer which represents the majority of heavy trucks on inter-city highways. The test load for this type of vehicle would need to be mechanically loaded – or unloaded - but this would have a positive effect of eliminating the need for local weigh scales for load mass measurement.

- Expand the maximum test speed to 110 km/h to replicate actual truck in-use cruise speeds[4].
- The mid point speed should be increased from 75 to 80 km/h test condition to correspond to typical posted speeds on urban arterial and undivided inter-city roads.
- The 60 km/h speed should be maintained for comparability and to maximize the variable range.

5. The number of test weight conditions could be reduced if simplifying assumptions about model linearity are used. Loads could be restricted to full and empty given the linearity of relationship between mass and rolling resistance.

6. Ideally all the data on road structure, roughness, grade and vehicle data would be collected simultaneously into a single data file. However, due to the irregular sampling period of the vehicle data system (a function of the Cummins engine control system) such a simultaneous data collect system is not possible. Therefore, at least two data files need to collected and merged through post analysis. Further, in researching the possibility of test vehicle-based collection of the IRI and grade information, it appears that while technically possible, it is financially impractical. Thus, it is recommended that the same data collection system as used in Phase 2 be used for any addition testing. This means that the vehicle (engine, wind, and road temperature), pavement roughness and grade will be collected independently of each other and then merged into a common file. It is thus very important the truck physical location on the test section is accurately measured. This was a problem especially on Quebec test sections in Phase 2 as they did not employ road distance markers. This can be solved with the use of temporary distance markers on the roadside. It may also be possible to use relatively low cost on-board GPS equipment to estimate road location to with a few metres resolution.

7. If improved data for input into vehicle power-based models is desired, then direct measurement of the rolling resistance coefficients on the various pavement test sites is required. This is problematic as there are only two ways of collecting the data:

   - Coast down tests which require the closure of long stretches of roadway as the speeds are well below posted minimums;
   - Use of a towed rolling resistance dynamometer which, while technically feasible, is not currently in existence. A unit was fabricated and tested in the early 1980's by Transport Canada but was abandoned due to lack of funding, high costs and very sensitive and unreliable instrumentation. Advances in computers and instrumentation may make the construction of a rolling resistance dynamometer more cost-effective and reliable now but its development would involve substantial non-recurring engineering design costs which could only be justified if there was an on-going pavement research program.

8. The statistical analyses undertaken in this study incorporate what the analysis team believes to be the most cost-effective set of analyses of the Phase 2 data set. We see little additional benefit from further analysis of this data. However, this study only used the test data for the semi-trailer configuration. There was additional data collected in summer conditions for a

4 as this speed is over the posted maximum Provincial agency approval would be needed to undertake the test.

straight tanker and a B-train tanker. These data sets could be analyzed to estimate the same type of regression models and in so doing possibly providing replication of the findings for the semi-trailer.