INVESTIGATION OF THE RELATIONSHIP BETWEEN DYNAMIC AXLE LOAD, ROUGHNESS AND FUEL CONSUMPTION

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ABSTRACT

The objective of the study described in this paper is to investigate a mechanistic relationship between roughness and Fuel consumption (FC). First, simulations of the response of a 5-axle tractor-semitrailer (5A-Semi) to real profiles with different roughness levels were performed to estimate the dynamic axle loads induced by each profile. Then, the Dynamic Load Coefficient (DLC) was computed every 0.03 km (0.02 miles). Finally, the FC of the truck was calculated and the recent HDM 4 model from the NCHRP 1-45 project was re-calibrated using DLC instead of the International Roughness Index (IRI) for each 0.03 km (0.02 miles) subsection. The analysis shows that the new model, after appropriate calibration, adequately predicted the effect of roughness on FC of the 5-axle Semi. Statistical analysis showed that there is no difference between the observed and the estimated FC at 95 percent confidence level.

INTRODUCTION

Understanding the costs of highway construction, highway maintenance and vehicle operation is essential to sound planning and management of highway investments, especially under increasing infrastructure demands and declining budget resources. While the infrastructure costs conceived by road agencies are substantial, the cost borne by road users are even greater. In 2009, the American Automobile Association *(1)* reported an average vehicle operating cost of 54.9¢ per vehicle mile (34.1¢ per vehicle km) based on 2008 prices. For conventional vehicles, these costs are related to fuel and oil consumption, tire wear, repair and maintenance, and depreciation. These costs depend on the vehicle class and are influenced by vehicle technology, pavement-surface type, pavement condition, roadway geometrics, environment, speed of operation, and other factors. Therefore, vehicle operating costs are part of the costs that highway agencies must consider when evaluating pavement-investment strategies.

Reduction in vehicle fuel consumption is one of the main benefits considered in technical and economic evaluations of road improvements considering its significance. According to the Bureau of Transportation Statistics (BTS), the 255 million vehicles in the United States consume about 760 billion liters (200 billion gallons) of motor fuel annually. With today's gas prices, this will translate to about 800 billion dollars. The fuel consumption of a vehicle is proportional to the forces acting on the vehicle. These forces are rolling resistance, gradient, inertial, curvature, and aerodynamic forces. It was reported that pavement conditions have great significance on rolling resistance forces. A decrease in pavement roughness by 3 m/km (190 in/mile) will result in a 10 percent decrease in rolling resistance *(2)*. A 10 percent reduction in average rolling resistance, promises a 1 to 2 percent decrease in the fuel consumption *(3)*. This would save about 7.6 to 15.2 billion liters (2 to 4 billion gallons) of fuel per year for the entire vehicle fleet. In this context, a 1 to 2 percent reduction in the fuel consumed would be a meaningful accomplishment.

A large body of research is available on the effects of pavement condition on vehicle operating costs and on models used to estimate these effects. Much of this information and many of the models were developed on the basis of data generated some years ago in other countries for vehicle fleets that vary substantially from those used currently in the United States and for roadways that differ from those built in the United States. A recent study *(4)* calibrated the HDM 4 fuel consumption model *(5)* to U.S. conditions. The research was conducted under project NCHRP 1-45. The recommended models reflect current vehicle technologies in the United States. The research focused only on the cost components that are mostly affected by pavement conditions, namely fuel consumption, repair and maintenance costs and tire wear. In this paper, we focused only on the effect of roughness on fuel consumption. The calibrated HDM 4 fuel consumption model is a mechanistic-empirical model; this type of model is more general and is capable of predicting the outcome for a wide variety of scenarios. However, the relationship between pavement condition and fuel consumption is an empirical equation. In this paper, a mechanistic-empirical approach to estimate FC using numerical modeling of vehicle response due to pavement surface profile is proposed.

BACKGROUND

The objective of the research performed under NCHRP Project 1-45 was to recommend models for estimating the effect of pavement conditions on Vehicle Operating Costs (VOC). The details of the research were reported in the NCHRP report 720 *(4)*. First, a large amount of data and information was collected, reviewed and analyzed to identify the most relevant fuel consumption models. The review was focused on research that has identified pavement surface conditions that affect fuel costs. Next, a large field investigation involving surveys to collect pavement condition data and field trials to collect fuel consumption data were conducted. These data were used to calibrate and validate the HDM 4 fuel consumption model and estimate the effect of pavement roughness on these components. Five different locations near Lansing, MI, were selected for field trials to reflect a wide range of pavement conditions (i.e., roughness, gradient, texture, and pavement type). Both asphalt and concrete pavements were included; IRI values for the test sections ranged from 0.8 to 8.5 m/km (51 to 539 in/mile); Mean Profile Depth (MPD) values ranged from 0.2 to 2.7 mm (0.01 to 0.1 in); grade ranged from -3.4 to 3.1%; and five speeds were considered. The tests were conducted during both winter wet and summer dry conditions. The actual weather conditions (temperature and wind speed) were recorded using a portable weather station. Tests were repeated when changes of more than 3°C (5°F) in ambient temperature were recorded. The pavement and weather test conditions were considered typical of those encountered in the US.

The pavement condition data (raw profile and texture depth) were collected by the Michigan Department of Transportation using a Rapid Travel Profilometer (ASTM E950-98) and a Road Surface Analyzer (ASTM E1845-09). In addition, slope data surveys were collected using a high precision GPS.

The sampling rate was every one second at highway speed (i.e., every 30.5 m or 100 ft). The average error of the measurement was 12.7 mm per 0.5 km (0.5 in. per 0.3 mile), i.e., 0.003 % (about twice the error of the total station). Six different vehicles that represent typical vehicles in the US were used. These were medium car, Sport Utility Vehicle (SUV), van, light truck (gas and diesel) and articulated truck. Tests for trucks were conducted using loaded and unloaded trucks. The light truck was loaded with two concrete blocks weighing a total of 2.82 metric tons (6,210 lb) according to the recommended payload. Both blocks were tightly secured to the truck bed. The trailer of the heavy truck was loaded with steel sheets (21.32 metric tons or 47,000 lb) also tightly secured to the trailer. The Gross Vehicle Weight (GVW) was about 36.3 metric tons (80,000 lb). Each vehicle had a data logger (scanner) connected to the OBD connector and the vehicle was driven at different speeds on cruise control to reduce the acceleration and deceleration cycles. Multiple and repeated runs were performed. In order to understand the effect of cruise control on the collected data, all the tests were conducted at constant speed with and without cruise control. The start and end points of data logging were marked by distinct flags and road markers.

The calibrated HDM 4 fuel consumption model was able to predict very adequately the fuel consumption of five different vehicle classes under different operating, weather and pavement conditions *(4)*.

RESEARCH METHODOLOGY TO CORRELATE DYNAMIC AXLE LOAD, ROUGHNESS AND FUEL CONSUMPTION

A road surface profile contains roughness waves or undulations of a length that, when driven over at a particular speed, produce an excitation in the vehicle at one of the vehicle's resonant frequencies. A normal vehicle is a simple mechanical vibrating system made up of the mass of the vehicle, the springs on which it rides, and the shock absorbers. At a particular frequency of vibration of bouncing of any vehicle, the vibration tends to increase in amplitude. At any particular speed of travel, there is a road profile wavelength that will excite the vehicle at one of its resonant frequencies and thus cause excessive vibration or bouncing. If the amplitude of that resonant wavelength is large, the vibration or vertical accelerations imparted to the vehicle may be quite noticeable. Since vertical accelerations impart significant vertical force, these wavelengths result in significant forces applied to the road, which can result in an increase in the traction forces applied to the vehicle *(6)*. Increase in the traction forces will result in increase in fuel consumption. An accurate prediction of roughness level that will excite trucks requires the evaluation of dynamic truck axle loading likely to be generated by the profile characteristics of the individual pavement section. One way to predict dynamic axle loads, given a surface profile, is to use a truck simulation computer program.

In this paper, a sensitivity analysis was performed to quantify the relationship between roughness and fuel consumption. The analysis consists of the following steps:

1. Simulation of the response of a 5-axle semi-truck to real profiles with different roughness levels.
2. Estimation of the total dynamic axle load for each roughness level;
3. Computation of the fuel consumption using the newly calibrated HDM 4 fuel consumption model by Chatti et al. *(4)*.
4. Computation of the coefficient of correlation between the predicted and measured fuel consumption using instrumented semi-truck.

Dynamic Vehicle Simulation

In general, most vehicles in a particular class possess similar characteristics and, for any particular road surface, most vehicles in the same class will be driven at about the same speed. The excitation of the vehicle becomes primarily a function of the wavelength content of the road profile surface *(6)*.

This section describes the analytical methods used to determine the dynamic response of the tractor-trailer combinations for purposes of determining the instantaneous wheel loads as they move along the road. The full vehicle model used in this study consists of tractor-semitrailers (articulated vehicles connected by a fifth wheel that allows pitch rotation). Together, tractor and trailer sprung masses have three degrees of freedom (d.o.f.); bounce of the tractor, pitch of the tractor, and pitch of the trailer. In addition, each of the axles has a bounce degrees of freedom. Thus, a 5-axle tractor-semitrailer is modeled with a total of eight degrees of freedom. The layout of a tractor-semitrailer is shown in Figure 1 as an example of the modeling. Parameter values for the tractor-semi trailer are presented in Tables 1 and 2. The raw profiles of 8 different sections with different roughness levels (Table 3) were input to the *TruckSim* software to predict the dynamic axle load for the 5-axle tractor-trailer combination. Since a large portion of heavy trucks have two dominant response modes – the body bounce at low frequency (1.5 to 4.0 Hz), and the wheel hop at high frequency (8.0 to 15.0 Hz), the default parameters in the *TruckSim* program were assumed.

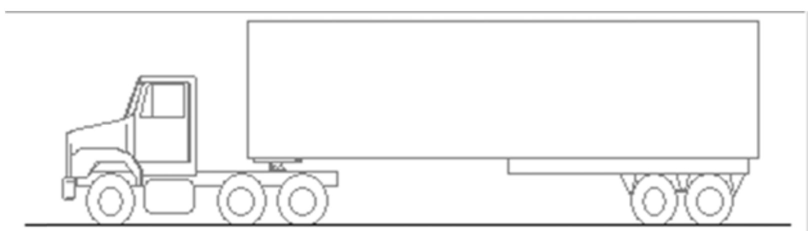


Figure 1: Typical mechanical model of a pitch-plane mode 5 axle truck

Table 1: Truck Matrix Sizes and Weights

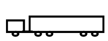
Truck Configuration	Configuration Name	GCVW (kN)	Axle Loads (kN)	Wheel Base (m)
	5 Axle Semi-Trailer	356	54/151/151	3.6/11.0

Table 2: Suspension Vertical Properties

Suspension Location	Suspension Type	Upper Envelope Stiffness	Lower Envelope Stiffness	β (Decay) Constan	Linear Damping Coefficient (kN-s/m)	Unsprung Weight (kN)
Steer Axle	Flat Leaf	28.5	28.5	0.04	0.50	6.2
Tandem Drive Axle	Flat Leaf	47.8	41.3	0.08	0.02	22.7
Tandem Semi-trailer Axle	Flat Leaf	47.8	41.3	0.08	0.02	16.9

Table 3: Test Section Information

Road	Start	End	Pavement Type		Length (km)	IRI range (m/km)	Speed (km/h)
			AC	PCC			
Creyts Rd	Lansing Rd	Millett Hwy	X		1.5	1.28-8.5	88
Creyts Rd	Millett Hwy	Mount Hope	X		1.6	1.7-7	88
Waverly Rd	Willow Hwy	Tecumseh river Rd	X		0.8	3.5-6	88
Waverly Rd	Tecumseh river Rd	Delta river Dr	X		0.8	3.25-6	88
M99 S	Holt Hwy	Columbia Hwy		X	6.4	0.8-4.8	88
M99 S	Bishop Rd	Holt Hwy		X	3.6		88

1 km = 0.6 mile; 1 mm = 0.04 in; 1 m/km = 63 in/mile; 1 km/h = 0.6 mph.

Calculation of the Fuel Consumption

The good quality of the data obtained in the NCHRP 1-45 study allowed the calibration and validation of the HDM 4 fuel consumption and engine speed models, and improved the estimation of the effect of roughness on fuel consumption. Therefore, the calibrated HDM 4 model is used in this study to estimate the fuel consumption. The model was calibrated assuming a constant mass, which is equivalent to the static load (as shown in Table 4). To incorporate dynamic load in the model, the instantaneous dynamic load was input to the HDM 4 model instead of a constant mass. Assuming flat and straight sections, the only remaining force is the rolling resistance force.

The predicted and measured fuel consumption using an OBD-II connector was compared in terms of (1) coefficient of correlation and (2) total consumption. The authors believe that since the HDM 4 model was calibrated using a static load, using the model with an instantaneous mass instead of a constant value will lead to unreliable results in terms of absolute values. Therefore, the authors decided to compare the normalized predicted and measured fuel consumption (Figure 2). The analysis performed to estimate the effect of roughness consists of the following steps:

1. Calculation of the total fuel consumption per section: The total fuel consumption per section was estimated by summing the instantaneous fuel consumption for each section.
2. Calculation of the total fuel consumption per unit length of 1 km: The total fuel consumption obtained in step 1 was divided by the section length.
3. Estimation of the effect of roughness using Equation 1. Note that the consumption for M99 S1 section was used as the baseline condition (IRI = 1.38 m/km or 88 in/mile).

$$AF_i = \frac{FC_i}{FC_{ref}} \quad (1)$$

Where:

AF_i = Adjustment factor for the fuel consumption at roughness level IRI_i

FC_i = Fuel consumption at roughness level IRI_i

FC_{ref} = Fuel consumption at the baseline conditions of IRI =1.38 m/km

Table 4: HDM 4 Fuel Consumption Model *(4)*

Name	Description	Unit
Fuel Consumption (FC)	$FC = \frac{1000}{\upsilon} * \left(\max\left(\alpha, \xi * Ptot\right)\right)$	mL/km
Y	Vehicle Speed	m/s
α	Fuel consumption at Idling	mL/s
ξ	Engine efficiency	mL/kW/s
Total power (P_{tot})	$P_{tot} = \frac{P_{tr}}{edt} + P_{accs} + P_{eng}$ for $P_{tr} \geq 0$, uphill/level $P_{tot} = edtP_{tr} + P_{accs} + P_{eng}$ for $P_{tr} < 0$, downhill	kW
Edt	Drive-train efficiency factor	dimensionless
$P_{engaccs} = P_{eng} + P_{accs}$	Engine (P_{eng}) and accessories power (P_{accs})	kW
Traction power (P_{tr})	$P_{tr} = \frac{\nu\left(Fa + Fg + Fc + Fr + Fi\right)}{1000}$	kW
Aerodynamic forces (Fa)	$Fa = 0.5 * \rho * CD * AF * \upsilon^2$	N
P	Mass density of the air	Kg/m^3
CD	Drag Coefficient	dimensionless
AF	Frontal Area	m^2
Gradient forces (Fg)	$Fg = M * GR * g$	N
M	Vehicle weight	Kg
GR	Gradient	radians
G	Gravity (Default = 9.81)	m/s^2
Curvature forces (Fc)	$Fc = \max(0, \frac{\left(\frac{M * \upsilon^2}{R} - M * g * e\right)^2}{Nw * Cs} * 10^{-3})$	N
R	curvature radius (Default = 3000)	m
Superelevation (e)	$e = \max\left(0, 0.45 - 0.68 * Ln\left(R\right)\right)$	m/m
Nw	Number of wheels	dimensionless
Tire stiffness (*Cs*)	$Cs = a0 + a1 * \frac{M}{Nw} + a2 * \left(\frac{M}{Nw}\right)^2$	kN/rad
a0 to a2	Model parameter	
Rolling resistance (F_r)	$Fr = CR2 * \left(b11 * Nw + CR1 * \left(b12 * M + b13 * \upsilon^2\right)\right)$	N
CR1	Rolling resistance tire factor	factor
Rolling resistance parameters (b11, b12, b13)	$\begin{cases} b11 = 37 * WD \\ b12 = 0.064 / WD \\ b12 = 0.012 * Nw / WD^2 \end{cases}$	parameters
WD	Wheel diameter	m
CR2	$CR2 = Kcr2\left[a0 + a1 * Tdsp + a2 * IRI + a3 * DEF\right]$	factor
Kcr2	Calibration factor	factor
a0 to a3	Model coefficient	dimensionless
Tdsp	Texture depth using sand patch method	mm
IRI	International roughness index	m/km
Deflection (*DEF*)	$DEF = (Tair / 30) * (-0.05 + 0.415 * e^{-0.08847 * \upsilon})$	mm
Inertial forces (F_i)	$Fi = M * (a0 + a1 * \arctan(a2 / \upsilon^3)) * acc$	N
Acc	Vehicle acceleration	m/s^2
a0 to a2	Model parameter	dimensionless

Comparison between Measured and Predicted Fuel Consumption

Table 5 presents the results of the comparison between the predicted and measured fuel consumption and the corresponding effect of roughness. The results show a reasonable agreement. The comparison between the cumulative predicted and the measured fuel consumption showed that the proposed approach was able of predicting the overall effect of roughness per section. It was observed that the predicted total fuel consumption per section matches well the measured total fuel consumption. However, from Figures 2 and 3, there is no correlation between the predicted and measured instantaneous fuel consumption (high bias, low accuracy). The poor correlation could be explained by the variability in the truck parameters. Since the truck parameters (such as the axle spacing, suspension properties, etc.) affect more the vibration around the mean than the mean in the axle dynamic load, the shorter the time step used in the instantaneous fuel consumption prediction, the higher the error when using typical values for truck parameters.

Table 5: Summary Statistics of the Predicted and Measured Fuel Consumption

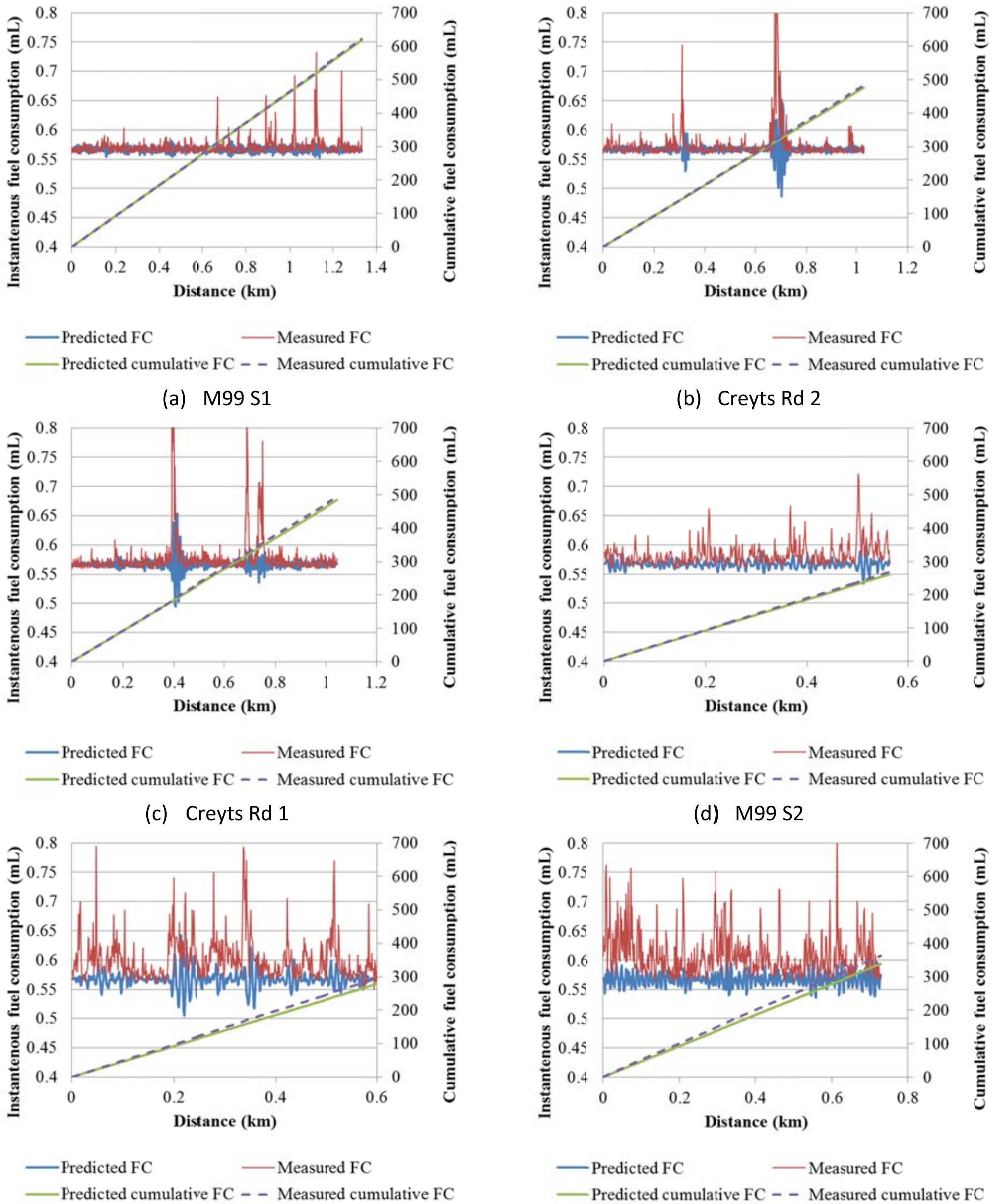
Parameter		**Road Name**					
		Creyts Rd 2	**M99 S 1**	**Creyts Rd 1**	**M99 S 2**	**Waverly Rd 1**	**Waverly Rd 2**
Roughness level (IRI, (m/km)		Smooth (1.38)	Smooth (1.77)	Medium (2.16)	Medium (2.68)	Rough (4.74)	Rough (5.33)
Length (km)		1332.2	1027.9	1045.0	563.4	609.9	729.7
Total fuel consumption/ section (mL)	P	618.1	476.9	489.9	266.4	297.0	361.6
	M	622.1	483.1	494.3	268.6	299.8	362.6
Total fuel consumption/ 1 km (mL)	P	464.0	464.0	468.8	472.9	486.9	495.6
	M	466.9	469.9	473.0	476.8	491.6	497.0
Effect of roughness	P	1.00	1.00	1.01	1.02	1.05	1.07
	M	1.00	1.01	1.01	1.02	1.05	1.06

METHODOLOGY TO CORRELATE DYNAMIC LOAD COEFFICIENT, ROUGHNESS AND FUEL CONSUMPTION

IRI is a good general indicator of pavement roughness. However, the range in dynamic truck axle loads for a given IRI value is wide, as shown in Figure 4 through the Dynamic Load Coefficient, DLC *(7)* and the 95th percentile of the dynamic axle load. The range is wider for higher roughness levels. This range exists because IRI was developed based on passenger car response to pavement surface. DLC is frequently used to characterize the dynamic loads generated by axles. It is a simple measurement of the dynamic variation magnitude of the axle load, for a specific combination of road roughness and speed. DLC is defined as the ratio of standard deviation over mean tire force:

$$DLC = \frac{\text{RMS of Dynamic tire force}}{\text{Static tire force}} = \frac{s}{P_0} \quad (2)$$

Thus the DLC can alternatively be interpreted as the coefficient of variation of the dynamic tire force. The DLC was computed every 0.03 km (0.02 miles) for all the sections in Table 5 using the generated axle loads. The DLCs values range from 5% to 30% (Figure 4). The DLCs are close to zero when the trucks are moving over a perfectly smooth road.



(a) M99 S1
(b) Creyts Rd 2
(c) Creyts Rd 1
(d) M99 S2
(e) Waverly Rd 1
(d) Waverly Rd 2

Figure 2: Predicted, measured instantaneous and cumulative fuel consumption.

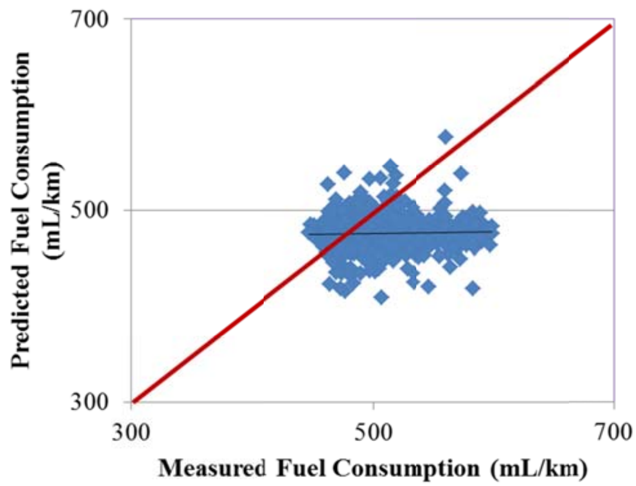


Figure 3: Predicted Versus measured instantaneous fuel consumption using dynamic axle load instead of static mass.

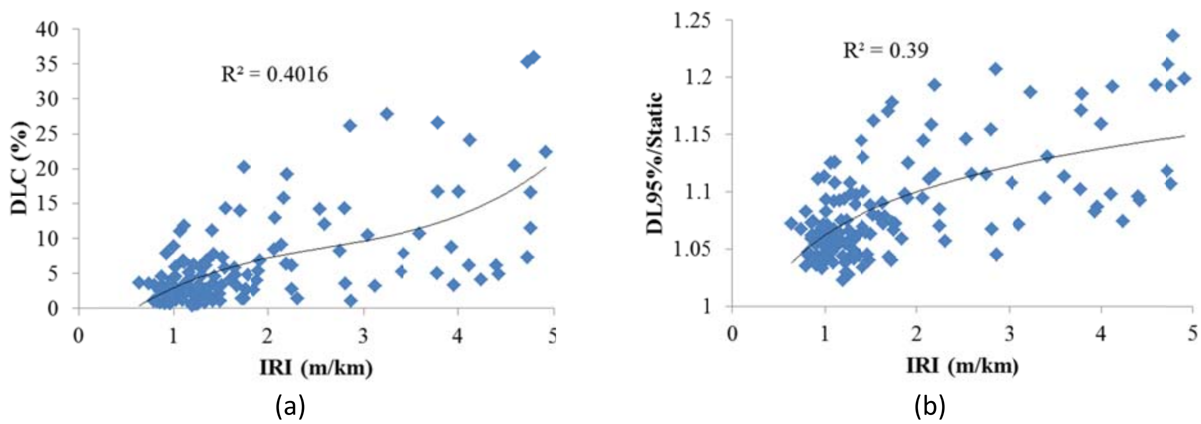


Figure 4: Relationship between (a) DLC and IRI; (b) Dynamic Load Amplification and IRI.

A sensitivity analysis was performed to quantify the relationship between dynamic axle coefficient and fuel consumption. The methodology consists of five steps:

1. Simulations of the response of a 5-axle tractor-semitrailer (5A-Semi) to real profiles with different roughness levels were performed to estimate the total dynamic axle load induced by each profile using the same approach as described above.
2. The dynamic axle load time histories obtained from step 1 were used to calculate the DLC every 0.03 km (0.02 miles).
3. The FC of the truck was calculated using the newly calibrated HDM 4 fuel consumption model from the NCHRP 1-45 project, except that DLC values calculated in step 2 were used instead of IRI.
4. The predicted instantaneous fuel consumptions from step 3 were compared to the measured values.
5. The HDM 4 fuel consumption model was calibrated by changing the value for a2 in the rolling resistance surface factor (CR2).

Incorporating DLC in the HDM 4 Model

The good quality of the data obtained in the NCHRP 1-45 study allowed the calibration and validation of the HDM 4 fuel consumption and engine speed models, and improved the estimation of the effect of roughness on fuel consumption. Therefore, the calibrated HDM 4 model is used in this study to estimate the effect of roughness on fuel consumption. Assuming flat and straight sections, the only remaining force in the HDM 4 model is the rolling resistance force. The HDM 4 use IRI as a measure for roughness level (as shown in Table 4). To incorporate dynamic load in the model, the FC of the truck was calculated using the newly calibrated HDM 4 fuel consumption using DLC values instead of IRI in the rolling resistance surface factor, CR2:

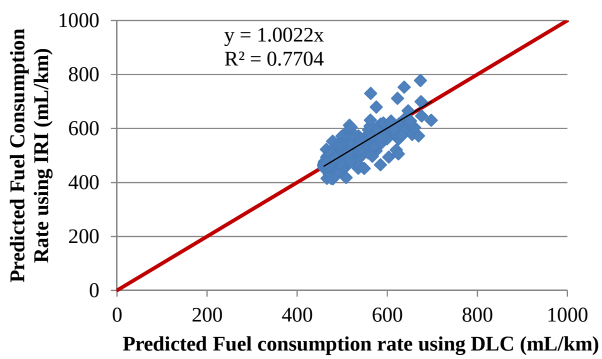
Old equation: $CR2 = Kcr2\left[a0 + a1*Tdsp + a2*IRI + a3*DEF\right]$ (3)

New equation: $CR2 = Kcr2\left[a0 + a1*Tdsp + a2*\mathrm{DLC} + a3*DEF\right]$ (4)

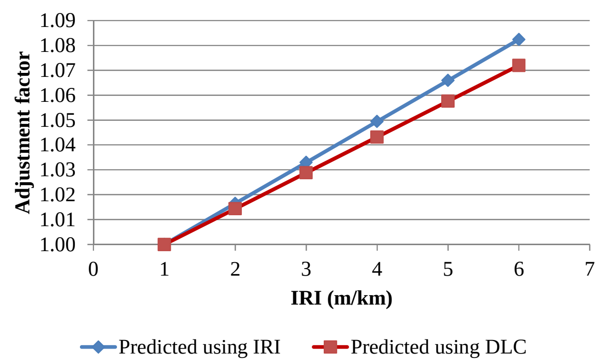
Then, the HDM 4 fuel consumption model with DLC was calibrated by changing the value for a2 in equation 4 until the lowest SSE between the predicted FC using HDM 4 with DLC and the FC using IRI is obtained.

Comparison between Predicted and Measured Fuel Consumption

Figure 5a presents the measured versus predicted fuel consumption after calibration. Statistical analysis showed that there is no difference between the observed and the estimated FC at 95 percent confidence level. Figure 5b presents the measured and predicted increase in fuel consumption using the newly calibrated HDM 4 model using DLC from the baseline condition of IRI = 1 m/km (63 in/mile) generated at 88 km/h (55 mph). For pavement management purposes, roughness was quantified using IRI. The analysis shows that an increase in the IRI of 1 m/km (63 in/mile) increases FC by 2% at 88 km/h (55 mph) for the 5-axle semi-truck. The use of DLC instead of IRI in the HDM 4 model improved the prediction of the effect of roughness on fuel consumption for trucks.



(a)



(b)

Figure 5: Predicted versus measured (a) instantaneous fuel consumption using DLC; (b) increase in fuel consumption due to roughness.

CONCLUSION

In this paper, we proposed a mechanistic approach to estimate the effect of roughness on fuel consumption. The proposed approach uses numerical modeling of vehicle response to estimate the dynamic axle load and the HDM 4 model to estimate the instantaneous fuel consumption. First, simulations of the response of a 5-axle tractor-semitrailer (5A-Semi) to real profiles with different roughness levels were performed to estimate the dynamic axle load induced by each profile. Then, the Dynamic Load Coefficient (DLC) was computed every 0.03 km (0.02 miles). Finally, the FC of the truck was calculated using the newly calibrated HDM 4 FC as part of the NCHRP 1-45 project using DLC instead of IRI for each 0.03 km (0.02 miles) subsection. The analysis shows that the new model, after appropriate calibration, adequately predicted the effect of roughness on FC of the 5-axle tractor-semitrailer. Statistical analysis showed that there is no difference between the observed and the estimated FC at 95 percent confidence level. The use of DLC instead of IRI in the HDM 4 model improved the prediction of the effect of roughness on fuel consumption for trucks.

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Part 2: Studies for materials and construction phases