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Analysis of Rolling Resistance Models to Analyse Vehicle Fuel Consumption as a Function of Pavement Properties

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1.1. Abstract

This paper presents an analysis of two recently developed models that relate pavement properties to vehicle rolling resistance and fuel consumption, as well as the sensitivity of each model to roughness, texture and future traffic predictions. The two models are the Vehicle Operating Cost model developed as part of the National Cooperative Highway Research Program (NCHRP) project 1-45 outlined in NCHRP report 720, and the model developed as part of an international collaboration, Models for rolling resistance In Road Infrastructure Asset Management systems (MIRIAM). Furthermore, several pavement related factors that contribute to vehicle rolling are discussed. It was found that the fuel consumption was highly sensitive to future traffic growth projections. Also, the pavement macrotexture can have a significant impact on excess fuel consumption of vehicles, particularly in the case that the MIRIAM model is used to calculate fuel consumption.

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1.2. INTRODUCTION

According to the Texas Transportation Institute (TTI), in 2011, congestion in the top US urban areas resulted in an average of 19 gallons of excess fuel consumption per auto commuter per year (Schrank et al. 2012). Although it is expected to be significant, there is no similar figure assessing the wasted fuel due to the trillions of vehicle miles travelled (VMT) over rough pavement sections that contribute to relatively high rolling resistance values. Rolling resistance is the mechanical energy loss by a tire moving a unit distance along the roadway, and is effected by both properties of the tire and of the pavement (Evans et al. 2009). The energy that is lost comes directly from the power that is used to propel the vehicle, and as a consequence, more fuel must be consumed to propel a vehicle over a pavement with higher rolling resistance. Evans et al. (2009) reported that as much as 1/3 of the total energy that is available to the wheels can be expended to overcome the rolling resistance. Other factors that consume the energy used to propel the vehicle (the energy that makes it to the driveline) are aerodynamic resistance and braking (TRB 2006).

Evans et al. (2009) measured the rolling resistance of several different tire types and reported that a 10 percent reduction in rolling resistance can lead to a 1 to 2 percent reduction in fuel consumption, with an average reduction of 1.1 percent. Schuring and Futamura (1990) have shown that this relationship can be taken as linear. TIAX (2003) reported that during highway driving, the 2 percent reduction in fuel consumption per 10 percent reduction in rolling resistance is expected, and the figure is closer to a 1 percent reduction during urban driving. Some estimations have shown that a 10 percent reduction in rolling resistance could save between 1 and 2 billion gallons of fuel annually (of 130 billion gallons currently consumed) among the passenger car fleet, assuming the driving habits used in the 2006 study (TRB 2006). Thus, it can be conclusively said that if the rolling resistance of a pavement were reduced, the vehicle fuel consumption along that pavement would also be reduced.

1.3. OBJECTIVE

The objective of this paper is to discuss the impact of pavement properties on vehicle rolling resistance, as well as present an analysis and comparison of current rolling resistance models. Two commonly used models to assess the additional vehicle fuel consumption due to rolling resistance will be compared, one model from the United States and one from Europe.

1.4. BACKGROUND

Many factors contribute to the fuel consumption of a vehicle, not the least of which is the interaction of the vehicle tire with the pavement surface. One of the earliest studies on the effects of road roughness on fuel consumption was performed in 1983 in Sweden by Sandberg at VTI (Swedish National Road and Transportation Research Institute) (Sandberg 1990). The study evaluated 20 different roadway characteristics representing the full range of Swedish roads at speeds of 50, 60 and 70 km/h (30, 37 and 45 miles/h). Vehicle fuel consumption was found to be correlated best with short wave unevenness ($r = 0.91$), mega-texture ($r = 0.83$) and macro-texture ($r = 0.60$).

Mega-texture is generally defined as a pavement surface texture due to surface irregularities having a relative wavelength between 5 cm and 0.5 meters (2 in and 20 in) (Flintsch et al. 2003). Pavement macro-texture is generally defined as a pavement surface texture having a relative wavelength between 0.5 mm and 50 mm (20 mils to 2 inches), and is a result of large aggregate particles in the mixture (Flintsch et al. 2003). It is important to note that macro-texture plays an important role in pavement friction. The short wave unevenness range is close to the wavelength sensitivity range of the IRI which is between 1.2 to 30 m (4 to 100 ft) (Sayers and Karamihas 1998). The following are pavement related factors that have been identified in past research as pertinent to consider during an analysis of the rolling resistance of the pavement: macro-texture, pavement stiffness, roughness, rutting and the transversal slope of the pavement (Santero et al. 2011; Sandberg et al. 2011; Chatti and Zaabar 2012).

1.4.1. Macro-Texture

Chatti and Zaabar (2012) evaluated the effect of pavement macro-texture on fuel consumption, and determined that an increase in fuel consumption with increasing mean profile depth of the pavement was statistically significant at the 95 percent confidence level for lower speeds. Laganier and Lucas (1990) found that macro-texture could lead to overconsumption of up to 5 percent from a base consumption of 0.7 l/km. At high speeds, it is expected that aerodynamic resistances dominate the resistance forces, thus causing the effect of macro-texture to be overshadowed. Conversely, Sandberg (1990) found that the effect of macro-texture on fuel consumption was more defined at higher speed; though the author pointed to a possible cause of low speed driving having a lower correlation as poorly selected driving conditions.

The increase in fuel consumption as a function of the pavement macro-texture is dependent on the vehicle type, and is expected to be higher for heavy vehicles. According to Sandberg (1990), the lower limit for expected effect of macro-texture on rolling resistance is a 2.5 percent increase in rolling resistance per unit increase of mean profile depth (in mm). Zaabar (2010) reported that for trucks, an increase in mean profile depth from 0.5 mm (0.02 in) to 3 mm (0.12 in) is expected to result in an increase in fuel consumption between 1 and 1.6 percent. Hammarström et al. (2008) used coast-down methods, or measurements of a vehicles velocity or acceleration while it is allowed to roll freely across a section of pavement, to measure the impact of pavement roughness, travel velocity and macro-texture on rolling resistance. The research proposed a set of equations to relate rolling resistance to macro-texture and roughness by comparing measurements taken during the research and theoretical models used to quantify the impact of each factor. The tests were conducted using a car, light truck and heavy truck. Some generalized results presented by Hammarström et al. (2008) are that an increase in rolling resistance of 17 percent per unit of mean profile depth is expected for a starting speed of 50 km/h for the car, and an increase of 30 percent per unit of mean profile depth is expected for a starting speed of 90 km/h for the car. The results showed that if the total driving resistance is considered, an increase in mean profile depth from 0 to 1 at 50 km/h is expected to lead to an increase of driving resistance of 10.5 percent for the car. The researchers noted that more measurements would be required to obtain results for the trucks.

1.4.2. Pavement Stiffness

Much of the research pertaining to the impact of pavement stiffness on rolling resistance has been derived from studies comparing asphalt concrete pavements to Portland cement concrete pavements. Taylor and Patten (2006) conducted field tests using both cars and heavy trucks driven over asphalt concrete pavements and Portland cement concrete pavements in order to evaluate differences in fuel consumption for each case. The research also tested over multiple seasons and the trucks were subjected to multiple loading conditions. In most cases, the results of the research showed anywhere from a 1 percent to a 5 percent savings in fuel consumption when driving on concrete pavements. However, during many of the tests during summer days, the research indicated a fuel saving for composite pavements when compared to concrete pavements (Taylor and Patten 2006). Although the test results indicated differences in fuel consumption with varying pavement stiffness, the developed models did not include surface wear and anomalies (e.g., potholes). Furthermore, other surface properties, such as tining of the concrete surface or texture of the pavement, were not accounted for in the study. Thus, the results of the study are not considered ideal for inclusion in an LCA of the use phase of the pavement.

Santero et al. (2011) evaluated the impact that the pavement stiffness has on the fuel consumption of a vehicle travelling along the pavement by developing a mechanistic model. The researchers proposed a beam on elastic foundation as the model to describe the behavior of the pavement subjected to a wheel load, and calibrated their model using data from the Long Term Pavement Performance (LTPP) database. The model indicated less fuel consumption over more stiff pavements, especially in the case of truck traffic. However, it is important to note that the model was developed in order to better understand the mechanisms that contribute to increasing rolling resistance with increased deflections, and field studies were not conducted to calibrate the model.

A follow up to the study by Santero et al. (2011) was conducted that calibrated the model that was developed to describe pavement deflections, and scaling factors were developed for each of the inputs (Akbarian et al. 2012). The calibration was conducted using additional sites from the LTPP database, and an example application of implementing the model into an LCA was conducted using data from the Athena Institute. The results of the study indicated that for high volume roads, the greenhouse gas (GHG) emissions from the pavement-vehicle interaction can be greater than the GHG emissions from the materials and construction phases (Akbarian et al. 2012).

Whereas much research has been conducted on the differences in pavement type on rolling resistance, Wang et al. (2012) pointed out that sufficiently validated models have yet to be developed to calculate the impact of pavement stiffness on fuel consumption and emissions. This is mainly a consequence of the experimental designs of the studies that compare asphalt pavements to concrete pavements. Although models were developed by Akbarian and Ulm (2012) as well as Santero et al. (2011) to quantify the impact of stiffness on fuel consumption, these models are generally considered first order attempts at understanding the mechanism of the pavement vehicle interaction, and are not yet sufficiently corroborated with field measurements to be used in a pavement LCA.

However, even in the absence of calibrated models, there is research demonstrating the differences in fuel consumption between asphalt and concrete pavements over certain conditions. Zaabar (2010) showed that at 35 mph (56 km/hr) during summer conditions, there is a statistically significant difference between vehicle fuel consumption along apshalt and concrete pavements for trucks. The development of more accurate models in the future will facilitate the inclusion of pavement type, or pavement stiffness, into a pavement use phase LCA.

1.4.3. Pavement Roughness

An early study on the impact of the pavement roughness on fuel consumption was conducted in 1983 in Sweden at VTI) (Sandberg 1990). The difference in fuel consumption between smooth and rough pavement was around 4.5 percent (EAPA/EuroBitume 2004). Laganier and Lucas (1990) found that pavement unevenness could lead to overconsumption of fuel of up to 6 percent from a base consumption of 0.7 l/km. Laganier and Lucas (1990) also calculated the power lost in the shock absorbers as a function of roughness level and found most loss occurs at wavelength between 1 m and 3.3 m which corresponds to the unevenness range as well as the most sensitive IRI range. According to Sandberg (1997), the lower limit for expected effect of roughness on rolling resistance is a 0.8 percent increase in rolling resistance per unit increase of IRI (in m/km).

In the United States, WesTrack test results showed that rougher pavements result in increased fuel consumption of trucks (Epps et al. 1999). Zhang et al. (2010) used the WesTrack models in the LCA of an overlay system. One downfall of the WesTrack model was that it was developed for heavy trucks over a small variation of conditions. Zaabar (2010) evaluated the impact of pavement roughness (in terms of IRI) on the change in fuel consumption, and used the data to calibrate HDM 4 prediction models.

Hammarström et al. (2008) also measured the impact of pavement roughness on rolling resistance using coast-down measurements. The research found that for the car, an increase in rolling resistance of 1.8 percent per unit of IRI is expected for a starting speed of 50 km/h, and an increase of 6 percent per unit of IRI is expected for a starting speed of 90 km/h. The results for the car showed that if the total driving resistance is considered, an increase in mean profile depth from 0 to 1 at 50 km/h is expected to lead to an increase of driving resistance of 1.2 percent. The researchers noted that more measurements are required to obtain results for trucks.

Chatti and Zaabar (2012) reported the results of calibrating the HDM 4 models for vehicle operating costs in the National Cooperative Highway Research Program (NCHRP) report 720. During this research, fuel consumption models as a function of pavement roughness for several vehicles and several speeds were calibrated. A vehicle operating cost modeling program was developed in the form of a spreadsheet tool by Chatti and Zaabar (2012) as a part of the NCHRP project. Part of the spreadsheet output is the estimation of the additional fuel consumption as a function of the following variables; pavement roughness, mean texture depth, roadway grade, super-elevation, pavement type (i.e., asphalt vs. concrete), vehicle speed and air temperature.

1.4.4. Rutting

Rutting was one of the variables analyzed in a VTI report aimed at using coast-down measurements to determine the effect of the road surface conditions on rolling resistance (Hammarström et al. 2008). However, rutting was not found to be significant on its own, and the researchers noted that the high correlation between rutting and the measured IRI may be good reason to leave rutting out of a generalized driving resistance model. The relationship between rutting and roughness has been demonstrated elsewhere (Mactutis et al. 2000), thus a separate factor relating rutting to rolling resistance would require rutting to be decoupled from the IRI effect if it was developed.

1.4.5. Transverse Slope

The transverse slope of the pavement, sometimes known as the crossfall or crossslope of the pavement, has an impact on the side forces of the vehicle, which in turn affects the rolling resistance along the pavement (Sandberg 2011). Although this feature of the pavement is recognized to impact rolling resistance, similar to superelevation, no significant amount of research exists to quantify its effects. However, Chatti and Zaabar (2011) included superelevation as a variable in the spreadsheet resulting from the NCHRP report 720, and it can be expected that the mechanism relating crossfall to rolling resistance behaves similar to the mechanism relating superelevation to rolling resistance.

1.5. ROLLING RESISTANCE MODELS

Two commonly used models relating pavement properties to rolling resistance and fuel consumption have been developed in recent years. One model was developed by Chatti and Zaabar (2012) by calibrating the HDM 4 models for vehicle operating costs. The fuel consumption model was calibrated over several pavements in the state of Michigan using six different vehicles: a medium car; sport utility vehicle; van; light truck and an articulated truck. The details of the model can be found in the NCHRP report 720 (Chatti and Zaabar 2012), along with a Microsoft Excel® tool developed as part of the NCHRP project that can be used to estimate vehicle operating costs (as well as vehicle fuel consumption) given several conditions.

The second model was developed as part of an international collaboration, Models for rolling resistance In Road Infrastructure Asset Management systems (MIRIAM), and is described in detail in Hammarstom et al. (2011). The model was developed based on empirical results from coast down measurements in Sweden, and includes impacts of: pavement roughness; macrotexture; temperature; speed; horizontal curvature and the road grade. The model was developed for three vehicle types: a car; a heavy truck and a heavy truck with a trailer.

1.5.1. Impact of Pavement Roughness on Vehicle Speed

An important variable that must be considered when evaluating fuel consumption as a function of pavement properties is the impact of the pavement roughness on the average vehicle speed. Hammarstom et al. (2011) investigated the impact of roughness on speed ffor European conditions. It is noted in Hammarstom et al. (2011) that reducing roughness may have the effect of increasing vehicle fuel consumption due to a corresponding increase in average vehicle travel speed. Yu and Lu (2013) investigated the relationship between roughness and speed and found that the average speed of a vehicle decreases 0.84 km/h for every increase in roughness of 1 m/km (0.0083 mph per every 1 in/mile). The data used in developing the relationship were taken from vehicles travelling along several pavement sections in California (both rigid and flexible pavements), and was limited to vehicles travelling between 80 and 145 km/hr (50 to 80 mph) to exclude times of congestion and vehicles that are potentially exceeding the speed limit by a significant amount.

1.6. ANALYSIS

In order to analyze and compare the two rolling resistance models, a baseline case of traffic was evaluated with the parameters shown in Table 0-1. The change in fuel consumption based on four variables will be evaluated: (1) the change in fuel consumption based on varying the roughness as a function of time; (2) the impact of the relationship between the reduction in average speed as a function of pavement roughness; (3)

sensitivity to traffic growth; and (4) sensitivity to macrotexture. The relationship between roughness and average speed given by Yu and Lu (2013) was included in the baseline calculations.

Table 0-1 Baseline Case for Evaluating the Models

Variable	Baseline Value	Variable	Baseline Value
Initial Roughness	0.87 m/km (55 in/mile)	Traffic (AADT)	30,000
Temperature	20° C (68° F)	Traffic Growth Rate (Compounding Interest)	3%
Horizontal Curvature	0	Medium Trucks	10%
Grade	0%	Articulated Trucks	15%
Crossfall	0%	Speed	105 km/h (65 mph)
Macrotexture	0.5 mm (0.02 inches)	Pavement Type	Flexible

A second order polynomial was assumed for the roughness growth model which (with IRI given in units of in/mile) as $a*(x)^2+b*(x)+c=IRI(x)$, where *IRI(x)* is the value of the IRI in year *x*, *c* was set at 55 in/mile, *b* was set as 1.23 in/mile/yr and *a* was changed to the following values [0, 0.15, 0.3, 0.45, 0.6], with a value of *a*=0 chosen as the baseline case for roughness. This value is taken from McGhee and Gillespie (2006) which reported a near constant growth in IRI of 1.23 in/mi-yr for a seven year time period for asphalt pavements in Virginia. The roughness growth over a ten year time frame can be seen in Figure 0-1 for each value of *a*. A ten year analysis period was evaluated, and the additional fuel consumption (i.e., the fuel consumption above the baseline case) was calculated per 1 km (0.62 miles) of pavement using the MIRIAM model (Hammarstom et al. 2011) as well as the software that accompanied the NCHRP report 720 (Chatti and Zaabar 2012). The results are shown in Figure 0-2 .

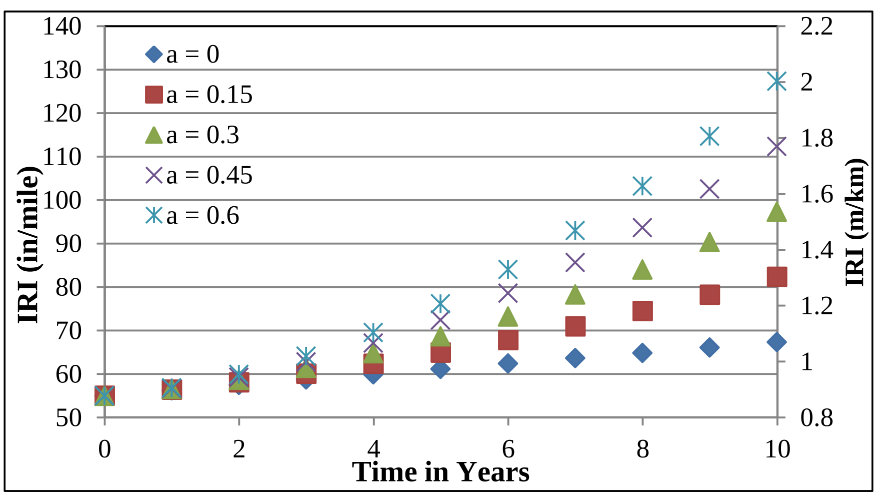

Figure 0-1 Roughness Growth Models

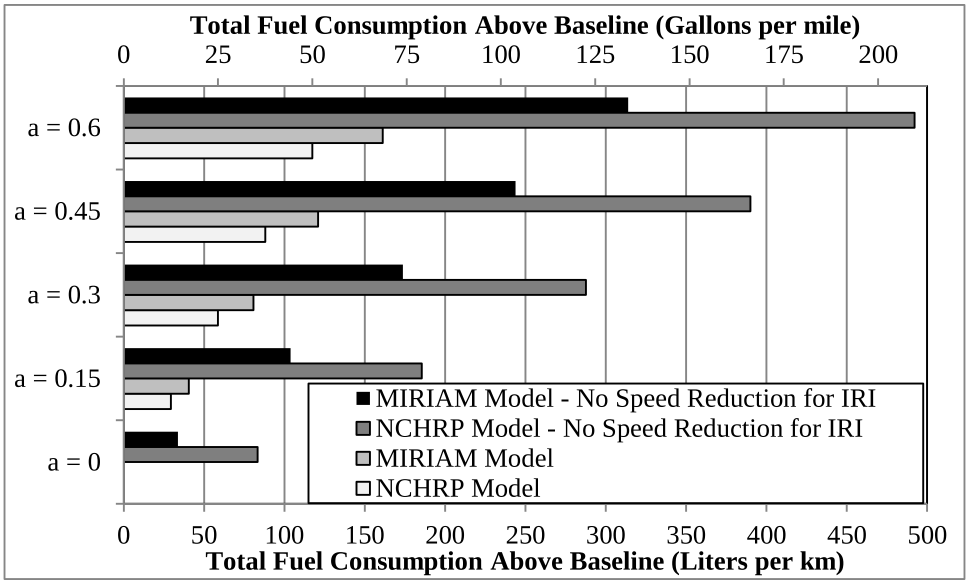

Figure 0-2 Fuel Consumption above Baseline Case as a Function of Roughness

It can be seen in Figure 0-2 that the NCHRP model is much more sensitive to the speed reduction due to an increase in IRI than the MIRIAM model. Although the models produce similar results, the highest amount of fuel consumption occurs when no speed reduction is taken into account and the NCHRP model is used. Conversely, the lowest amount of fuel consumption occurs with the NCHRP model when the speed reduction is taken into account. Next, the influence of macrotexture on the excess fuel consumption was calculated, assuming the baseline case of 0.5 mm (0.02 in), and a constant growth in roughness of 0.02 m/km/yr (1.23 in/mile/yr) per McGhee and Gillespie (2006). The results can be seen in Figure 0-3.

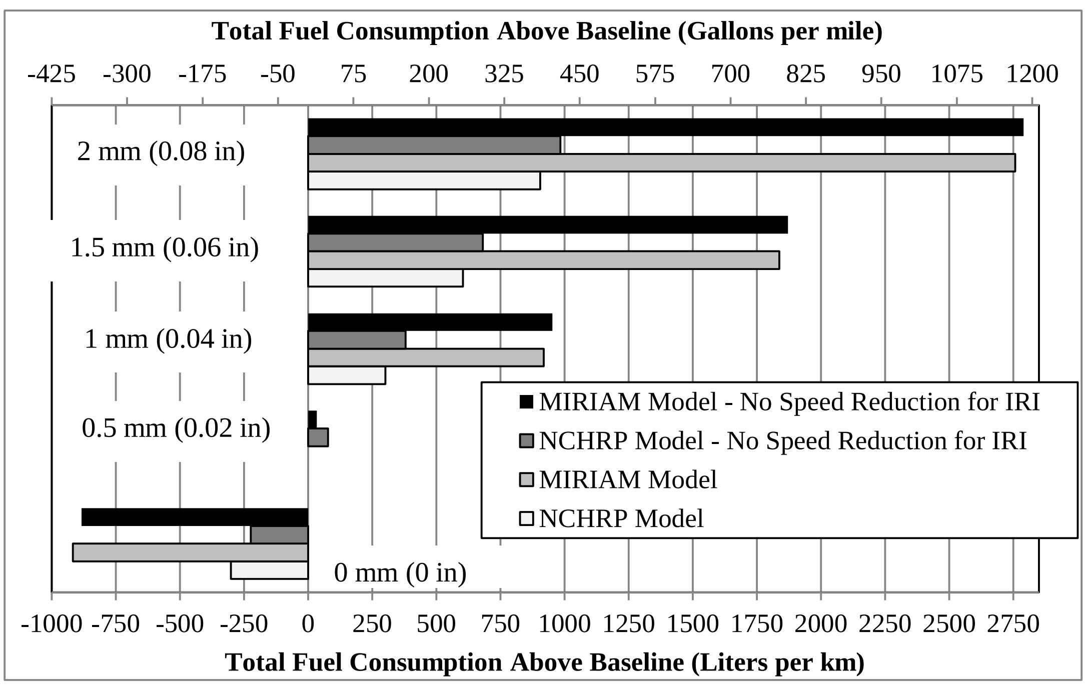

Figure 0-3 Fuel Consumption above Baseline Case as a Function of Macrotexture

It can be seen in Figure 0-3 that the MIRIAM model is much more sensitive to changes in macrotexture than the NCHRP model. Also, the difference between the case where the speed reduces as a function of IRI and the case where no speed reduction is considered is nearly insignificant when compared to changes in the values for macrotexture. Finally, the influence of the traffic growth rate (compound growth) on the excess fuel consumption above the baseline case was evaluated, and the results can be seen in Figure 0-4.

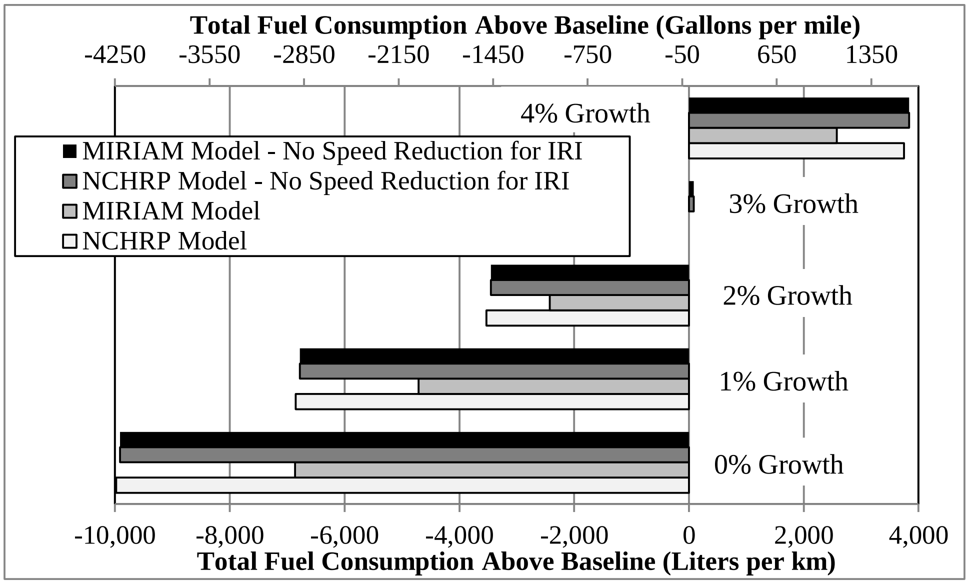

Figure 0-4 Fuel Consumption above Baseline Case as a Function of Traffic Growth (Using Compound Growth)

Of the four variable analysed (IRI growth, macrotexture, speed reduction as a function of IRI and traffic growth rate), it can be seen that the traffic growth rate most significantly impacts the excess fuel consumption. This seems to indicate that if a transportation agency has the goal of reducing fuel consumption within a pavement network, the most influential factor of those that were analyzed is to reduce the number of vehicles travelling in the network in future years. Second to the traffic growth rate is the macrotexture of the pavement. However, it is important to note that macro-texture plays an important role in pavement friction (Flintsch et al. 2003), as well as an important role in controlling pavement noise.

In order to better represent the sensitivity of the fuel consumption on the macrotexture, roughness and speed for each model, the three variables were plotted on the same figure for values that yield the same fuel consumption (Figure 0-5 and Figure 0-6). The value for fuel consumption chosen as the iso-plane was taken as the baseline case (defined in Table 0-1). One notable result is that the NCHRP model is more sensitive to changes in the average vehicle speed than the MIRIAM model (as seen by the smaller variation in speed in Figure 0-5). Secondly, both models produce flat planar surfaces, as opposed to having curvature.

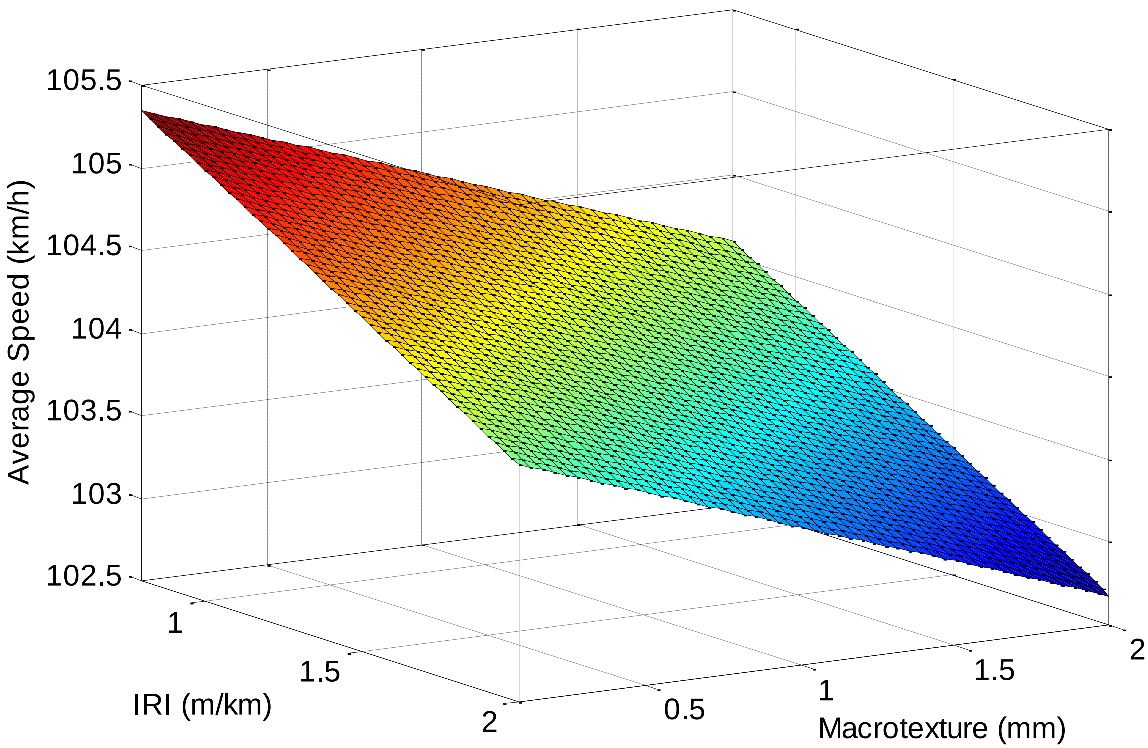

Figure 0-5 Surface for Constant Fuel Consumption Using the NCHRP Model

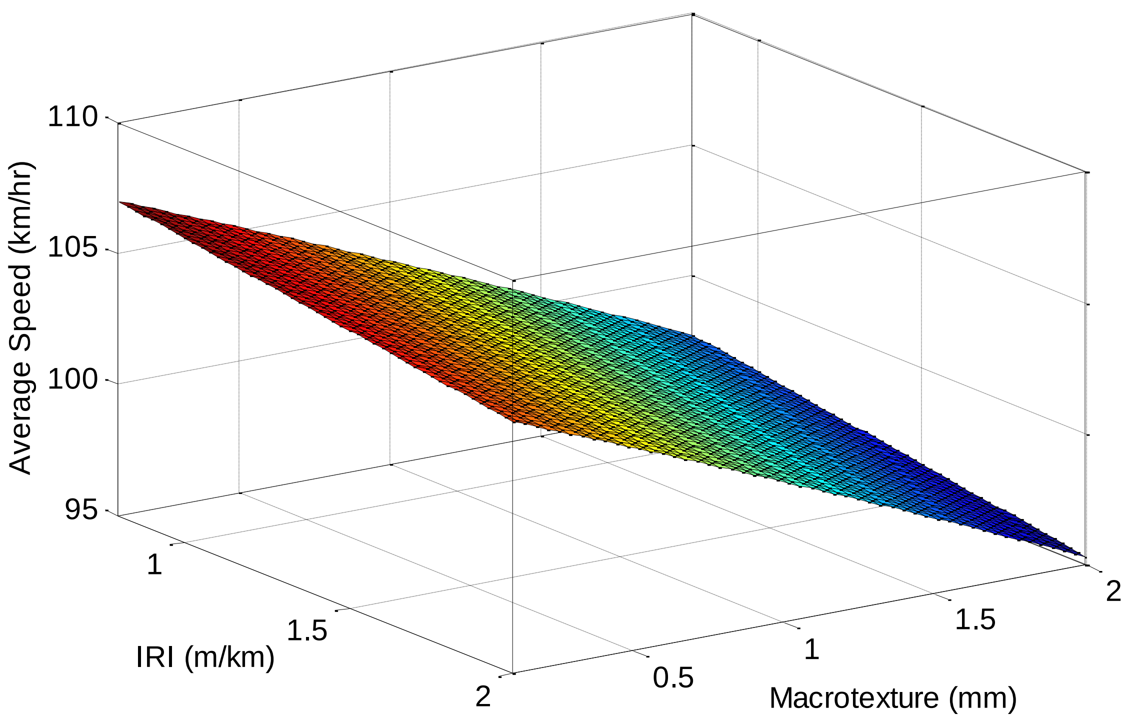

Figure 0-6 Surface for Constant Fuel Consumption Using the MIRIAM Model

1.7. DISCUSSION AND CONCLUSIONS

Models that relate vehicle rolling resistance to pavement properties can prove to be a valuable resource for transportation agencies, particular when they are concerned with analyzing such factors as the impact of excessive roughness on fuel consumption or the potential value of smoothness to road users. This paper presented two recently developed models, as well as an evaluation of their sensitivity to variables pavement roughness, pavement macrotexture and average vehicle speed. It is clearly shown that small variations in average speed can have a much more significant impact on the vehicle fuel consumption than the typical range of pavement roughness or macrotexture. Also, it was found that the total excess fuel consumption was highly sensitive to future traffic growth projections. Furthermore, the pavement macrotexture has a significantly higher impact on excess fuel consumption of vehicles than pavement roughness for both models analyzed.

1.8. ACKNOWLEDGEMENTS

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