MAPPING PAVEMENT-VEHICLE INTERACTION LIFE CYCLE IMPACTS ON VIRGINIA'S INTERSTATE SYSTEM

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ABSTRACT

The sustainable development of our nation's roadway system requires quantitative means to translate pavement structural and performance data into Greenhouse Gas (GHG) emissions. The recent developments of mechanistic pavement-vehicle interaction models aim at such quantitative engineering estimates. Herein, we illustrate how these models can be used at the network level through application to data collected by Virginia DOT. It is shown that the mapping of the excess-fuel consumption due to roughness and deflection induced PVI can provide an additional metric for maintenance and rehabilitation scheduling for roadway agencies, based on GHG emissions at the network scale.

INTRODUCTION

The US roadway network is incredibly large and has significant impact on the environment. Based on recent data there are more than 4 million miles of public roads that lead to 1.45 billion metric tons of Carbon Dioxide (CO_2) each year. This equates to over 27% of total US Greenhouse Gas (GHG) emissions *(1)*. Together, these numbers demonstrate the magnitude of the investment in public roadways and their impact on the environment. They also emphasize the importance of developing rigorous quantitative models that assess the environmental footprint of pavements and conditions within the US, in order to reduce the carbon footprint of pavements.

One main contributor to a pavement's life cycle environmental footprint, especially for high traffic volume roadways, is Pavement-Vehicle Interaction (PVI). It is the impact of pavement condition and design on vehicle fuel economy, induced by rolling resistance from pavement surface texture, roughness, and its structural deflection. Although the impact of PVI is small for a single vehicle, it is shown that the aggregated impact for the high traffic volume roadways is a major contributor in the life cycle footprint of pavements. Hence, there is a growing need for use of PVI models to assess the pavement performance to reduce the carbon footprint of the roadway network by guiding carbon management and fuel savings.

The impact of roughness and deflection induced PVI are captured by models developed to relate pavement condition, structural and material properties to the resulting excess fuel consumption. Pavement roughness is related to excess fuel consumption using the calibrated HDM-IV model *(2)*. To capture the impact of deflection-induced PVI, a mechanistic model is developed that relates pavement structural and material properties to changes in fuel consumption, by capturing pavement viscoelasticity, temperature, and speed effects *(3-5)*.

In this paper, we apply roughness and deflection induced PVI models to data from the Virginia Interstate system, and assess the excess fuel consumption and carbon emissions due to pavement roughness as well as its material and structural properties. The impact of PVI in Virginia's interstate system is compared to the US roadway network for a variety of pavement design systems, including asphalt, concrete, and composite sections. Moreover, pavement sections that lead to excess fuel consumption due to PVI are identified throughout the network.

PVI MODELS

Various empirical and mechanistic investigations have studied the impact of pavement deflection and roughness on vehicle fuel consumption. They conclude that vehicles consume less fuel on pavements with higher stiffness and lower roughness, but fail to establish a link between pavement structural and material properties and change in fuel consumption *(2,6-13)*. Although empirical studies on PVI deflection suggest an impact on fuel consumption from pavements exists, there is no consensus in its suggested magnitude. Here we present the deflection and roughness induced PVI models used for this analysis.

Deflection-Induced PVI

Excess fuel consumption due to deflection-induced PVI is calculated by the model developed by Louhghalam et al. *(3,4)*. The model relates pavement material and structural properties to the rolling resistance due to pavement deflection. The pavement is modeled as a viscoelastic beam on an elastic foundation subjected to a moving load with a constant speed. To maintain this speed, extra power is provided by the vehicle to overcome the dissipated energy δE due to the viscoelasticity of the beam, leading to excess fuel consumption. The deflection-induced PVI model calculates the excess energy consumption as a function of vehicle speed *c,* vehicle load P, and the temperature and material dependent relaxation time $\tau(T)$ as *(3,4)*:

$$\delta E = \frac{c_{cr}}{\boldsymbol{c}} \times \frac{\boldsymbol{P}^2}{bk\ell_s^2} \times F\left(\frac{\boldsymbol{c}}{c_{cr}}; \frac{\boldsymbol{\tau}(\boldsymbol{T})c_{cr}}{\ell_s}\right) \tag{1}$$

Where:

δE is the dissipated energy due to the pavement deflection as a function of two invariants, $\boldsymbol{c}/c_{cr}$ and $(\boldsymbol{\tau}(\boldsymbol{T})\ c_{cr})/\ell_s$. Here, c_{cr} is the critical speed, b is width of the beam, k is the elastic subgrade modulus, and $\ell_s = (\frac{Eh^3}{12}/k)^{1/4}$ is the Winkler length of the beam with top layer modulus E, and top layer thickness h. It is worth noting that the dissipated energy relates to the square of vehicle load $\delta E \propto P^2$ and the inverse of vehicle speed $\delta E \propto \sim 1/c$. Meanwhile, an increase in temperature, results in change in the complex modulus of the viscoelastic pavement, leading to an increase in the dissipated energy. The variation in pavement material properties due to temperature is modeled and calculated separately for asphalt and concrete pavements.

Roughness-Induced PVI

The impact of pavement roughness on fuel consumption has been extensively studied *(2)*. Research has developed various indices to represent pavement roughness. International Roughness Index (IRI), which is the accumulated suspension motion of the quarter-car per distance traveled, is the one typically used for this purpose. IRI is evaluated from longitudinal profile of the pavement and has the units of slope: in/mile *(14)*. Zaabar and Chatti *(2)* have investigated the impact of pavement roughness on fuel consumption and calibrated the World Bank's Highway Design and Maintenance Standards Model (HDM-IV) for 5 vehicle classes in the US. This model relates pavement IRI to its impact on fuel consumption so that:

$$\delta E = E_c(IRI - IRI_{\mathrm{m}}) \tag{2}$$

Where:

δE is the change in excess fuel consumption for a single vehicle, E_c is the vehicle specific percentage change in fuel consumption due to a unit increase in IRI *(3)*, and IRI_m is the pavement reference roughness after maintenance. The value of IRI_m is a pavement management policy decision on the roughness of new pavements and is assumed $IRI_m = 63$ *in./mile*. Higher values of IRI_m decrease ride quality and reduce the number of roads that contribute to excess fuel consumption.

NETWORK ANALYSIS

The models for roughness and deflection induced PVI are used to calculate the excess fuel consumption on Virginia's interstate highways and make comparisons to national averages in the US roadway network.

Data for pavement condition and design in Virginia were collected from the Virginia Department of Transportation (VDOT), and includes information on five pavement types in the interstate system: Bituminous (BIT), Jointed Reinforced Concrete Pavement (JRCP), Continuously Reinforced Concrete Pavement (CRCP), Bituminous over JRCP (BOJ), and Bituminous over CRCP (BOC). The data on pavement type, LTPP equivalent sections, and pavement lengths are summarized in Table 1. The data also includes information on:

- Section Identifier and milepost.
- Pavement roughness (IRI) for 2007-2013.
- Annual Average Daily Truck Traffic (AADTT) for 2007-2013.
- Section Layer structure and thicknesses for 2007-2013.
- Material properties for 2007.

The distribution of different types of pavements in the interstate pavement system of VA is displayed in Figure 1a. It can be observed that asphalt pavements dominate the network, followed by composites, and finally concrete pavements. The corresponding truck traffic load (AADTT) for these sections are displayed in Figure 1b.

Table 1: Pavement Types and Lengths Analyses within the Virginia Interstate System.

Type	VA Label	LTPP Equivalent	Lane-mile	Center-mile
Asphalt (AC)	BIT	GPS 1,2	3,131	1,416
Concrete (PCC)	JRCP CRCP	GPS 4 GPS 5	360 130	119 55
Composite (Com)	BOJ BOC	GPS 7 GPS 7	854 366	294 165

Condition of the US roadway network is determined using data from Federal Highway Administration's Long Term Pavement Performance (LTPP) program *(15)*. The data consists of over 800 pavement sections from in-service General Pavement Studies (GPS) sections. These pavements include asphalt concrete (AC), Portland cement concrete (PCC), and composite pavements that also correspond to pavement types in Virginia.

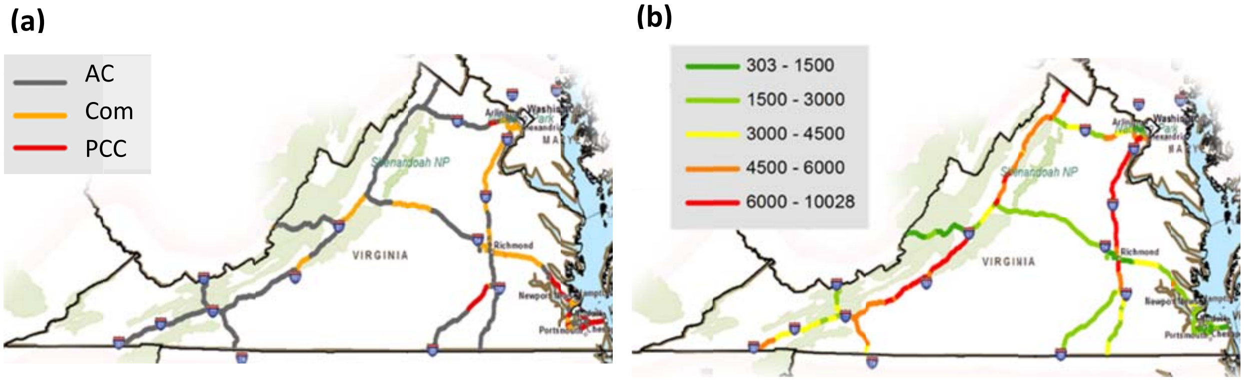

Figure 1: The interstate pavement system in VA represented by (a) pavement type (b) annual average daily truck traffic (AADTT).

MODEL APPLICATION AND RESULTS

The models for deflection and roughness induced PVI are here applied to pavement sections in the VA interstate system, and the impact on excess fuel consumption (FC) and greenhouse gasses due to PVI are investigated. Moreover, pavement conditions and their impact on PVI in Virginia are compared to the national averages obtained from LTPP.

Deflection-Induced PVI

To calculate the impact of deflection-induced PVI on fuel consumption, model input parameters are determined from structural data obtained through Falling Weight Deflectometer tests performed in VA in 2007. They are used to calculate the excess fuel consumption and investigate temperature effects on PVI in Virginia's interstate system. More specifically, values for the top layer and subgrade moduli E and G_s, as well as the pavement thickness h are used for analysis of each milepost of each interstate. The distributions of these inputs are reported here and approximately follow a lognormal distribution with their mean and standard deviations presented in Table 2.

Table 2: Mean and standard deviation of the corresponding normal distribution for pavement modulus *E* (in ln(MPa)), subgrade modulus G_s (in ln(MPa)) and pavement thickness *h* (in ln(m)) for VA pavement types.

Type	$\mu_{ln}(E)$	$\sigma_{ln}(E)$	$\mu_{ln}(G_s)$	$\sigma_{ln}(G_s)$	$\mu_{ln}(h)$	$\sigma_{ln}(h)$
Asphalt (AC)	8.17	0.96	4.34	0.40	-1.26	0.16
Concrete (PCC)	11.2	1.34	3.97	0.47	-1.87	0.43
Composite (Com)	12.2	1.01	3.82	0.34	-1.54	0.15

Temperature and Speed Sensitivity

There are fundamental differences in the viscoelastic behavior of asphalt and concrete and their corresponding relaxation time $\tau(T)$, leading to temperature dependent mechanical properties for viscoelastic material. The time-temperature superposition principle is used to establish this temperature dependence and find the material relaxation time at any given temperature *T* from the relaxation time measured at a reference temperature T_{ref} :

$$\tau(T) = a_T \times \tau(T_{ref}) \tag{4}$$

where a_T is the shift factor calculated from the Arrhenius law for concrete pavements *(16)*:

$$log\ a_T(T) = U_c \left[\frac{1}{T} - \frac{1}{T_{ref}}\right] \tag{5}$$

and from William Ferry Landel equation for asphalt pavements *(17)*:

$$log\ a_T(T) = \frac{-C_1(T-T_{ref})}{C_2+(T-T_{ref})} \tag{6}$$

This results in different variation of dissipation due to changes in temperatures and vehicle speeds, and therefore the resulting fuel consumptions due to PVI. Here we investigate the impact of temperature variations on vehicle fuel consumption in Virginia. Figure 2 shows the impact of changing speed and temperature on vehicle fuel consumption, throughout a year for VA asphalt and concrete pavement sections.

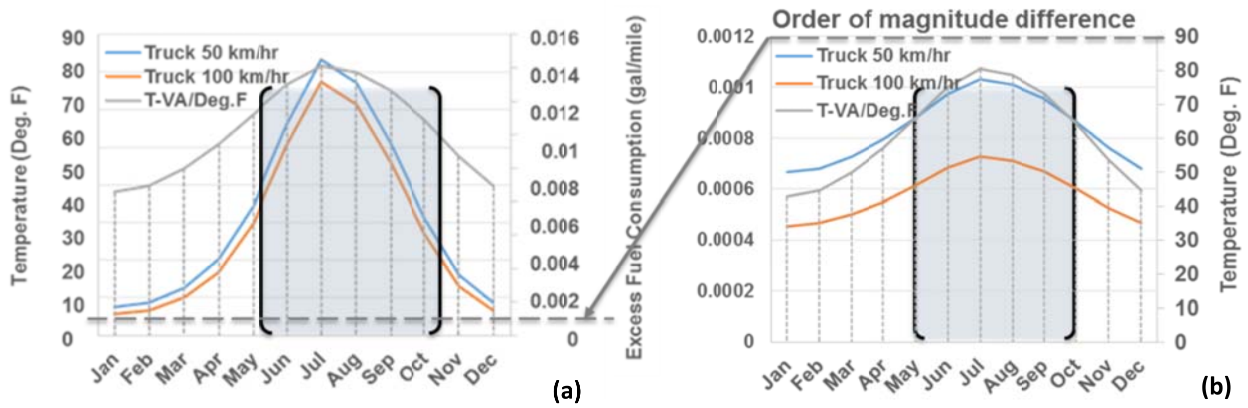

Figure 2: Calculated impact of monthly air temperature variations on a HS20-44 truck fuel consumption in Virginia at 50 km/hr and 100 km/hr for (a) asphalt (b) concrete pavements.

Temperature data are state averages obtained from the National Oceanic and Atmospheric Administrations *(18)*. It is shown that lower vehicle velocity results in higher fuel consumption due to higher viscoelastic dissipation. Deflection-induced PVI is highly temperature dependent, with lowest values in months of January and December and highest in July and August, showing an order of magnitude range in impact.

Deflection-Induced Fuel Consumption

The excess fuel consumption due to deflection-induced PVI is calculated at the average annual state temperature T=61 Deg. F, for a HS20-44 truck, for bituminous, composite, and concrete pavements. The impact is calculated for each milepost of each interstate, using their corresponding top layer and subgrade moduli and the top layer thickness. A statistical analysis of these values, presented in Figure 3, compares the probability distribution of vehicle fuel consumption across the VA interstates. The excess fuel consumption is calculated in reference to a non-dissipative pavement system. It is shown that concrete pavements induce the lowest excess fuel consumption, followed by composite pavements, and an order of magnitude higher by asphalt pavements. These results are expected given the viscoelastic properties of asphalt. The final excess fuel consumption, considering traffic volume is presented in Figure 4 for each section.

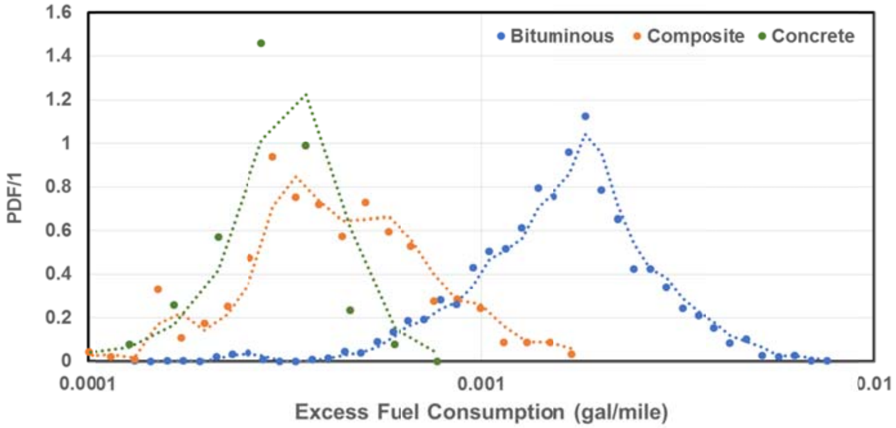

Figure 3: Unit area probability density function of the calculated deflection induced excess fuel consumption within the VA interstate system.

Given for a HS20-44 truck at speed of 62 mph on bituminous, composite, and concrete pavements. Average annual state temperature T=61 Deg. F.

Roughness-Induced PVI

The impact of roughness-induced PVI on fuel consumption is estimated herein. The main input parameter for the model is pavement roughness represented by IRI, and is used in the HDM-IV model to calculate roughness-induced excess fuel consumption.

IRI in VA Interstate

The probability distribution function of pavement roughness, recorded in terms of IRI, is used to determine the cumulative distribution function (CDF) of pavement roughness in both Virginia's interstate system and the US roadway network as illustrated in Figure 5a. The results indicate that the roads in VA are maintained to a lower roughness IRI_m (see Eq. 1) compared to the average US distributions. Figure 5b shows the breakdown of roughness CDF functions for asphalt, concrete, and composite pavements in VA.

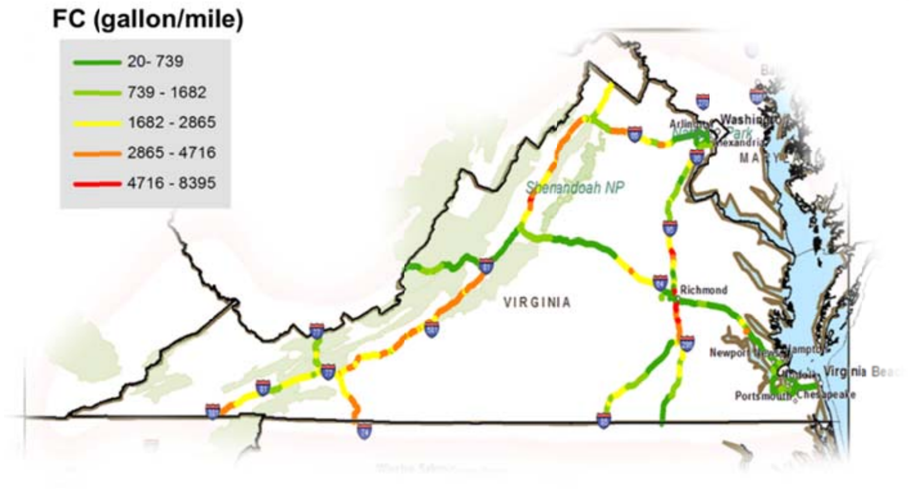

Figure 4: 2013 excess fuel consumption in Gallon/mile, due to deflection-induced PVI of trucks on Virginia's Interstate system, considering AADTT, at speed of 62 mph, and average annual state temperature T= 61 Deg. F.

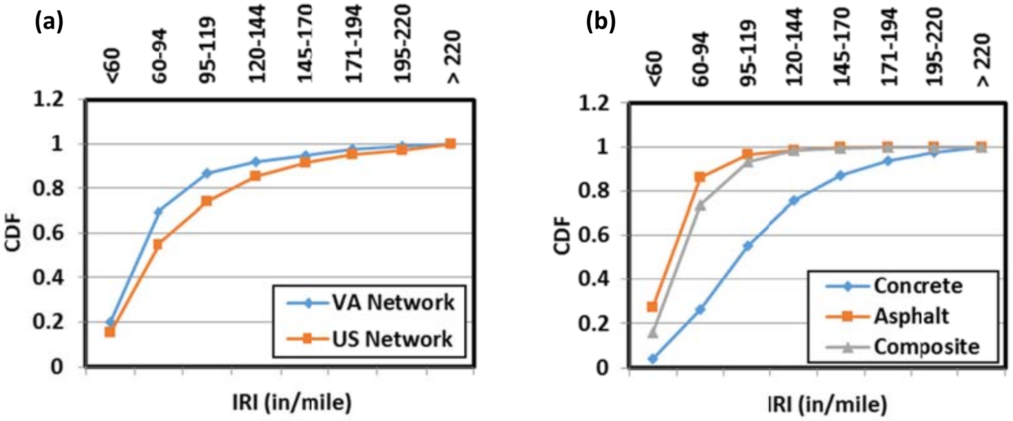

Figure 5: Roughness (IRI) in the VA interstate network in 2013. (a) VA interstate roughness compared to the national average (b) IRI breakdown of VA pavement types.

It is observed that asphalt and composite pavements are maintained to an approximately equal roughness threshold, IRI_m, while concrete pavements have statistically higher roughness levels across the network. This can be due to a number of factors including pavement age, stage in life cycle, and timeframe of analysis. Asphalt and composite pavements are maintained and resurfaced more frequently than concrete pavements. Also, the shorter service life of asphalt and composite pavements and their more frequent maintenance needs, allows capturing most of their life cycle in the 7 year analysis period. Concrete pavements on the other hand, are maintained with longer periods between maintenance treatments.

Roughness-Induced Fuel Consumption

IRI distributions along with traffic volume for each section and post-mile were used to calculate the excess fuel consumption for Virginia's interstate system, and are shown in Figure 6. High roughness, and high traffic areas, e.g. around Richmond, observe the most increase in excess fuel consumption due to roughness.

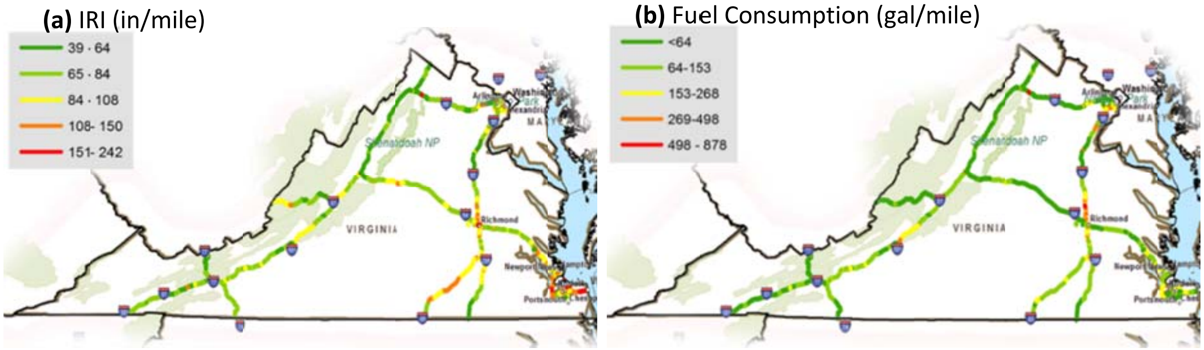

Figure 6: (a) Roughness distribution in terms of IRI (in/mile) in the VA interstate network (b) Excess fuel consumption of trucks (gallons/mile) due to roughness-induced PVI in the VA interstate network in 2013.

Total Annual Fuel Consumption

The total PVI impact from roughness and deflection is calculated and displayed in terms of excess fuel consumption (gallon/mile) in Figure 7. Figure 8 presents the annual excess fuel consumption and GHG emissions due to both deflection and roughness induced PVI. It allows for comparison of contributions of roughness and deflection to PVI, and it is shown that both contribute on the same order of magnitude within the network throughout the analysis period. Due to the lower than average roughness levels in VA, as shown in Figure 5a, the roughness induced PVI impacts are lower than the average US. It is worth noting these results are for a HS20-44 truck, which has a significantly larger impact on PVI deflection excess fuel consumption than roughness. Addition of passenger vehicles into the analysis would create a better understanding of use phase LCA impacts.

Figure 7: Annual excess fuel consumption per mile due to deflection and roughness induced PVI of trucks on Virginia's interstate system. Roughness data are from 2013 and deflection data are from 2007.

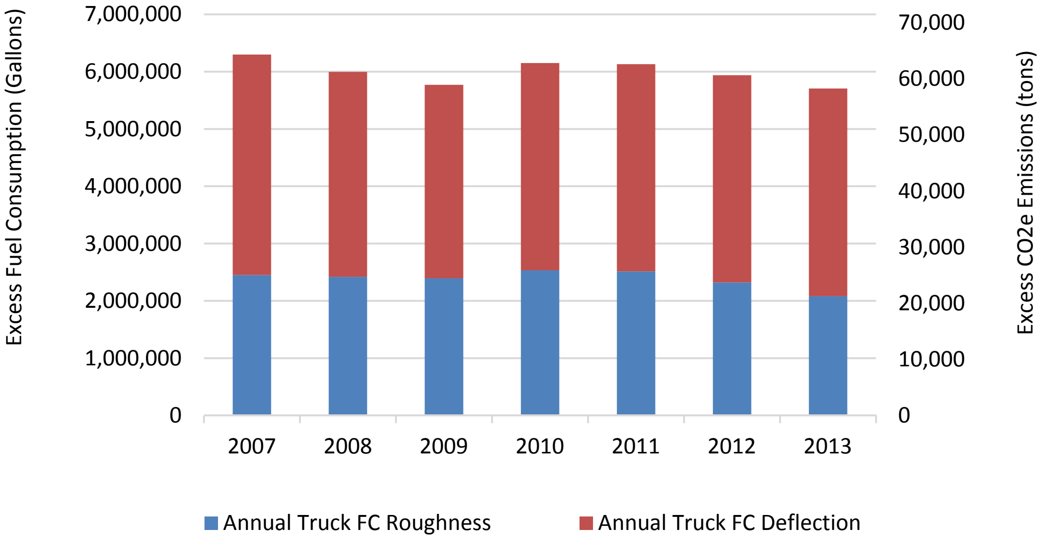

Figure 8: Total annual excess fuel consumption due to deflection and roughness induced PVI within the VA interstate system for the analysis period of 2007-2013 and a HS20-44 truck.

CONCLUSION

Recent developments of mechanistic PVI models allow estimating excess fuel consumption within the roadway network. The models are easily implementable and require a minimum amount of input parameters which are typically available to agencies, yet at different scales (IRI, structural, and material data). As such, the models can be used to identify means to reduce the environmental impact of a roadway network; and can serve as an additional criterion for maintenance scheduling and pavement management. Furthermore, the mapping of the excess fuel consumption and associated GHG emissions will only be helpful to decisions makers at local, state, or federal levels if used through a life cycle analysis perspective to enhance the sustainability of the roadway network. Lastly, further expansion of pavement management and information data by transportation agencies can go a long way in making confident network level decisions.

ACKNOWLEDGEMENTS

This research was carried out as part of the Concrete Sustainability Hub at MIT, supported by the Portland Cement Association (PCA) and Ready Mixed Concrete (RMC) Research and Education Foundation. Data for the Virginia interstate system analysis was provided by the Virginia Department of Transportation (VDOT) and the Virginia Center for Transportation Innovation & Research.

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