Roughness-Induced Pavement–Vehicle Interactions

ROUGHNESS-INDUCED PAVEMENT-VEHICLE INTERACTIONS: KEY PARAMETERS AND IMPACT ON VEHICLE FUEL CONSUMPTION

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Abstract: Pavement roughness affects rolling resistance, and thus vehicle fuel consumption. In fact, when a vehicle travels at constant speed on an uneven road surface, the mechanical work dissipated in the vehicle's suspension system is compensated by vehicle engine power, resulting in excess fuel consumption. This dissipation depends on both road roughness and vehicle dynamic characteristics. Herein we propose, calibrate and implement a mechanistic model for roughness-induced dissipation. The distinguished feature of our model is that it combines a thermodynamic quantity (energy dissipation) with results from random vibration theory in order to identify the governing parameters that drive the excess fuel consumption due to pavement roughness; namely the international Roughness Index (IRI) and the waviness number, w (a Power Spectral Density parameter). It is shown via sensitivity analysis that the sensitivity of model output, i.e. the excess fuel consumption, to the waviness number is significant and comparable to that of IRI. Thus, introducing the waviness number as a second roughness index, in addition to IRI, allows a more accurate quantification of the impact of surface characteristics on vehicle fuel consumption and the corresponding greenhouse gas emission. This is illustrated by an application of our roughness-fuel consumption model to two road profiles extracted from FHWA's Long Term Pavement Performance (LTPP) database.

INTRODUCTION

It has long been recognized that pavement roughness affects the pavement vehicle interaction (PVI), and contributes to the vehicle operating costs (VOC) (*1,2*). The most prominent VOC model is the HDM4 model which relates a measurable pavement roughness parameter, the International Roughness Index (IRI) introduced originally for quantifying ride comfort (*3,4*), through empirically calibrated vehicle-dependent functional relations, to fuel consumption (*5,6*). Such VOC models have recently gained some new importance within the context of engineering life-cycle-assessment (LCA) methods of pavement structures that relate pavement condition to rolling resistance and corresponding fuel consumption and environmental impacts (*7*). This background provides motivation for this study that aims at identifying the key parameters for roughness-induced fuel consumption.

More specifically, roughness-induced fuel consumption is due to energy dissipation in vehicle's suspension system: when a vehicle travels at constant speed on an uneven road surface, the mechanical work dissipated in the vehicle's suspension system is compensated by additional vehicle engine power. Thus, a mechanistic model of the actual energy dissipation is expected to provide a direct means to relate pavement roughness and vehicle-specific physical quantities to fuel consumption. This is shown in the first part of this paper. Instead of using a single value roughness index, such as IRI, we employ the roughness power spectral density (PSD) as a refined means to describe the distribution of roughness across various wavelengths. We then show how this mechanistic model can be calibrated when using the HDM4-model. Finally, by way of application, the novel VOC model is employed using road profiles extracted from FHWA's Long Term Pavement Performance (LTPP) database, and the difference between our prediction and the HDM4 model in terms of dissipation and fuel consumption is discussed.

THEORETICAL BACKGROUND: MECHANISTIC MODEL FOR ROUGHNESS-INDUCED PVI

For a first-order evaluation of the energy dissipation by a vehicle's suspension system, we consider the classical two-degree-of-freedom (2-DOF) quarter-car model (*8*) (Figure 1(a)): a two-mass system in series composed of a tire (stiffness k_t) and a spring-dashpot parallel suspension unit (stiffness k_s and viscosity coefficient C_s). The dissipation of mechanical work into heat form is only due to the relative motion, $\dot{z} = dz/dt$ (with z the relative displacement of sprung mass m_S with respect to the unsprung mass m_u) of the suspension system, i.e. $\delta D = C_s \dot{z}^2$; or when expressed in terms of the expected value of energy dissipated per traveled length at constant speed V:

$$\mathrm{E}[\delta\mathcal{E}] = \frac{C_s}{V}\mathrm{E}[\dot{z}^2] \quad (1)$$

The suspension motion $\dot{z} = dz/dt$ is due to road roughness transmitted from the ground via tire stiffness k_t. It is generally assumed that road roughness ξ is a zero-mean stationary Gaussian process (*9*). In practice the power spectral density of road profile is represented as a power function of the angular wavenumber, Ω (*10*):

$$S_\xi(\Omega) = c|\Omega|^{-w} \quad (2)$$

where the unevenness index, c, and the waviness number, w, characterize the road profile. In fact, Eq. (2) is a linear function in logarithmic space with slope w for which the larger values indicate the presence of longer wavelengths. The use of a PSD representation allows the employment of random vibration theory to link the mean square of suspension motion in Eq. (1) to both dynamic properties of the vehicle and roughness parameters (*11*):

$$\mathrm{E}[\dot{z}^2] = \int_0^\infty V^2\Omega^2 |H_s(V\Omega)|^2 S_\xi(\Omega) d\Omega \quad (3)$$

where $H_s(\omega)$ is the dimensionless frequency response function (FRS) that relates the relative suspension deformation to the road roughness profile:

$$H_s(\omega) = \frac{\omega^2 k_t m_s}{(-m_u\omega^2+iC_s\omega+k_t+k_s)(-m_s\omega^2+iC_s\omega+k_s)-(iC_s\omega+k_s)^2} \quad (4)$$

with $\omega = V\Omega$ the angular frequency. The above FRS depends only on dynamic properties of vehicle (quarter-car in case of simple 2-DOF model) while roughness PSD carries the information on pavement surface characteristics.

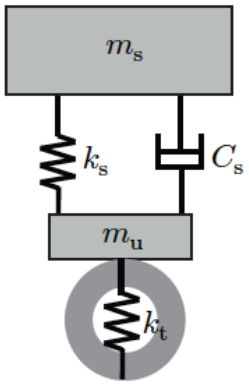
Thus, combining equations (1) and (3), the expected value of dissipated energy per unit length traveled is obtained in a form that relates the dissipated energy in the car suspension to road surface properties via roughness PSD parameters (i.e. waviness number w and the unevenness index c) as well as vehicle properties via FRS:

$$\mathrm{E}[\delta\mathcal{E}] = cC_sV \int_0^\infty \Omega^{2-w} |H_s(V\Omega)|^2 d\Omega \quad (5)$$

Or, in terms of the circular frequency:

$$\mathrm{E}[\delta\mathcal{E}] = cC_sV^{w-2} \int_0^\infty \omega^{2-w} |H_s(\omega)|^2 d\omega \quad (6)$$

Recognizing that the argument inside the integral of Eq. (6) does not depend on vehicle speed, the energy dissipation is found to scale with the vehicle speed as $\mathrm{E}[\delta\mathcal{E}] \sim V^{w-2}$. That is, for waviness numbers, $w > 2$, the roughness-induced dissipated energy increases with the speed, and for $w < 2$ it is the inverse. We keep this scaling in mind for later applications.



(a)

Property	value
k_t/m_s $[s^{-2}]$	653
k_s/m_s $[s^{-2}]$	63.3
C_s/m_s $[s^{-1}]$	6.0
m_u/m_s $[1]$	0.15

(b)

FIGURE 1 (a): 2-DOF Quarter-car model; (b): dynamic properties of the golden-car used for evaluation of IRI.

At this stage of the development, it is appropriate to close the loop with other roughness-induced VOC models based on the International Roughness Index (IRI), such as the HDM4-model (*5,6*)

for vehicle fuel consumption and related GHG emissions. To this end, we remind us that IRI is defined as the average rectified velocity of a specific quarter-car (golden-car) traveling at $V_0 = 22.2$ m/s (80 km/h):

$$\mathrm{IRI} = \frac{1000}{V_0 L}\int_0^L |\dot{z}_{GC}|dx \tag{7}$$

where the subscript GC denotes the golden-car properties, given in Figure 1(b). Assuming the road profiles are stationary Gaussian processes, the expected value of IRI can be written in terms of roughness PSD parameters in the form (*11*):

$$\mathrm{E[IRI]} = \sqrt{\frac{2}{\pi}V_0^{w-3} c \int_0^{\infty} \omega^{2-w}|H_{s-GC}(\omega)|^2 d\omega} \tag{8}$$

where H_{s-GC} is the FRS of the Golden Car. A final substitution of Eq. (8) into Eq. (6) provides the following expression for the energy dissipation:

$$\mathrm{E}[\delta\mathcal{E}] = \frac{\pi}{2} C_s V_0 \times \left(\frac{V}{V_0}\right)^{w-2} \times \frac{\int_0^{\infty} \omega^{2-w}|H_s(\omega)|^2 d\omega}{\int_0^{\infty} \omega^{2-w}|H_{s-GC}(\omega)|^2 d\omega} \times \mathrm{E[IRI]}^2 \tag{9}$$

Expression (9) is of particular interest in order to fully appreciate the added value of the mechanistic-based roughness-induced PVI model compared to other empirical models. Specifically, the dissipated energy scales with the square of (the expected value) of IRI; and also depends on the waviness number, w. Hence, a calibration of the model requires consideration of (at least) a second pavement roughness parameter, in addition to IRI. This is shown here below.

CALIBRATION WITH HDM4 MODEL

The mechanistic roughness-induced PVI model in expression (9) relates surface characteristics to roughness-induced energy dissipation and the resulting excess fuel consumption by using a simple 2-DOF system as a quarter-vehicle model. In reality the dynamic behavior of vehicles is far more complicated to be comprehensively captured by a single quarter-car model. While inertial properties (such as sprung and unsprung masses) of the vehicle can be estimated with reasonable accuracy, the stiffness properties are not easy to evaluate; since the total stiffness involved in different components of a vehicle is more complex than the stiffness of suspension and tire.

As an alternative, and in the absence of such detailed measurements, we use the HDM4 model (*5,6*) to calibrate our mechanistic roughness-induced PVI model. Such a calibration aims at determining the stiffness properties for the different vehicle classes, together with the road waviness number as an additional adjustable parameter. In the HDM4 model the variation of excess fuel consumption due to a unit change in IRI is reported for different driving speeds and for five vehicle classes: medium car, SUV, Van, light truck and articulated truck. The properties of these vehicles, obtained from literature are summarized in Table 1. To calibrate the model, we use total fuel consumption evaluated from HDM4 model at reference $\mathrm{IRI}_0 = 1$m/km as baseline, $\mathrm{IFC}_0 = \mathrm{IFC}(\mathrm{IRI}_0)$, and convert roughness-induced dissipated energy evaluated from equation (9) to excess fuel consumption using an engine efficiency coefficient (ξ_b in mL/kW/s, given for the vehicle classes in Table 1):

$$E[\delta\mathrm{IFC}] = \xi_b E[\delta\mathcal{E}] \tag{10}$$

The percent change in fuel consumption due to change in IRI relative to reference IRI_0 using the mechanistic model is thus evaluated:

$$\frac{E[\delta\mathrm{IFC}(\mathrm{IRI})]-E[\delta\mathrm{IFC}(\mathrm{IRI}_0)]}{\mathrm{IFC}_0}\times 100 \tag{11}$$

The corresponding data points $\mathrm{IFC}(\mathrm{IRI},\mathrm{V})/\mathrm{IFC}_0-1$ from calibrated HDM4 model is also obtained for IRI values varying from 1 to 6 m/km and vehicle speeds 56-112 km/h associated with the range of vehicle speed in field measurements (*5*). Model calibration is performed by minimizing the difference between the predicted change in excess fuel consumption from the two methods by adjusting a single value for waviness number w and five dimensionless stiffness-mass coefficients $\beta_j=\sqrt{k_t m_s/(k_s m_u)}$ for each vehicle class. The results of the optimization procedure are illustrated, for the five vehicle classes, in Figure 2 for two vehicle speeds, 70 and 100 km/h, in form of plots of the total fuel consumption vs. IRI, comparing our results with the predictions of the HDM4 model (*5*). Unlike the HDM4 model that relates the excess fuel consumption linearly to IRI, the mechanistic model presented here establishes a functional relationship between the excess fuel consumption and the square of IRI, observed both in Eq. (9) and Figure 2. The fitted dimensionless coefficients β_j are summarized in Table 1. Furthermore, the waviness number obtained in the optimization procedure is $w=2.4117$, which agrees well with the probability distribution of waviness number w of the Long-Term Pavement Performance (LTPP) program of the US Federal Highway Administration (FHWA) reported by Kropac and Mucka (*12*), which exhibits a mode at around $w=2.5$. We consider this agreement as an independent validation of our modeling approach of roughness-induced PVI.

TABLE 1 Vehicle Dynamical Properties Given per Axel. (❖: CarSim Template, ◆ :GMC Specification Manual)

Car class Properties	Medium Car	SUV	VAN	Light Truck	Articulated Truck
m_t(ton)	1.46 (*4*)	2.5 (*4*)	2.54 (*4*)	6.5 (*4*)	34.9 (*4*)
m_s (kg)	80 (*19*)	125❖	134 (*20*)	395◆	544 (*21*)
k_s (KN/m)	29.44 (*19*)	189❖	48	337 ◆	700 (*21*)
ξ_b	.096 (*4*)	.072 (*4*)	.072 (*4*)	.062 (*4*)	.059 (*4*)
β	46.98	28.03	31.00	14.90	13.30

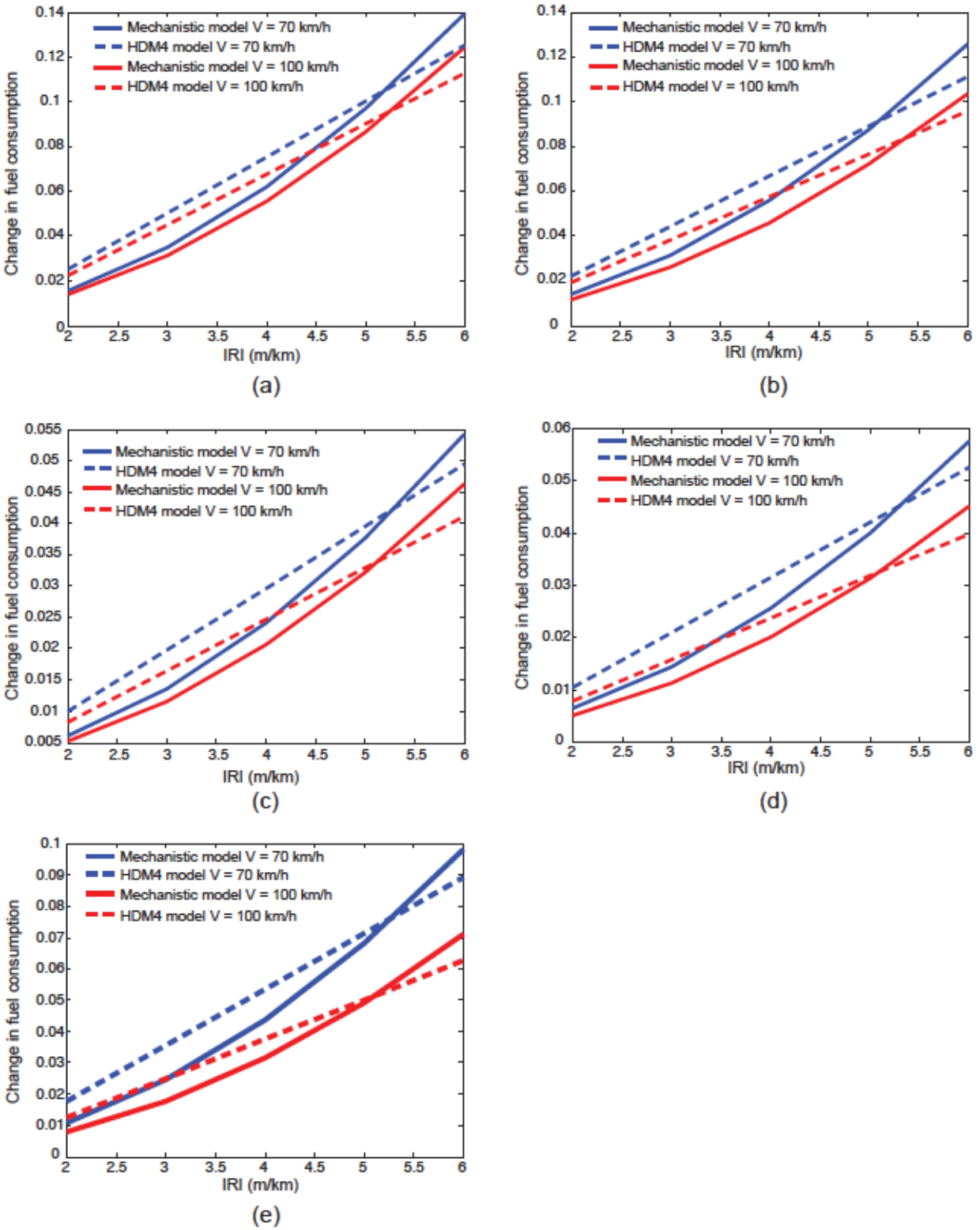


FIGURE 2 Roughness-induced change in fuel consumption in function of IRI at V=70 and 100 km/h for (a): medium car; (b): SUV; (c): van; (d): light truck and (e): articulate truck.

SENSITIVITY ANALYSIS

To complete this investigation of roughness-induced PVI, it is instructive to investigate the sensitivity of the model-based estimated excess fuel consumption w.r.t. the uncertainty in model input parameters. Such a sensitivity analysis aims at identifying the main factors driving the uncertainty of model output and quantifies the associated contribution. Herein, we use the Spearman rank correlation coefficient (SRCC) (*13*) to determine the sensitivity of the energy dissipation to input parameters of the roughness model. The SRCC method falls under the large category of global sensitivity analysis, which – in contrast to local sensitivity analysis – provides information about the sensitivity of the model output to all input variables across the entire design space and accounts for the interaction between different input parameters. To this end, we perform Monte-Carlo simulations by generating realizations of input parameters according to their distribution in the roadway network. Using the roughness mechanistic model in equation (9) for each realization we evaluate roughness-induced dissipation and relevant fuel consumption. We then use this result to evaluate SRCC between each input parameter and the excess fuel consumption.

Monte-Carlo Simulation

The calibrated roughness-induced dissipation model in Eq. (9) is characterized by three independent inputs parameters: IRI, waviness number (w) and vehicle speed (V). To perform Monte-Carlo simulation these input parameters must be generated according to their probability density functions (PDFs).

For the distribution of IRI and waviness number, we use the results of the empirical distributions of the LTPP program of the US FHWA dataset reported by Kropac and Mucka (*12*). As shown in Figure 3, the PDFs of both IRI and waviness number follow respectively a lognormal and a truncated normal distribution with mean and standard deviation summarized in Table 2. The probability density function for vehicle speed is evaluated from the Highway Fuel Economy Driving Schedule (HWFED) provided by the US Environmental Protection Agency (EPA), which represents highway driving conditions for vehicles traveling under 60 mph (*14*). Since our model is developed under the steady state assumption for constant vehicle speed, the vehicle speeds associated with stop and go condition, i.e. speeds lower than 30mph at the beginning and end of speed time history, are filtered out for PDF estimation (see Figure 4).

To generate a random number with cumulative distribution function (CDF) $F_X(x)$ we use the inverse transformation technique: first a random variable U with uniform distribution $U\sim u[0,1]$ is generated. It can be readily shown that the inverse of the cumulative distribution function evaluated at U, $X = F_X^{-1}(U)$, is a random variable with CDF $F_X(x)$. The technique is used here to generate random variables from parametric distributions shown in Figure 3 (lognormal for IRI and truncated normal for waviness number) as well as the non-parametric empirical PDF illustrated in Figure 4(b) for vehicle speed. A total number of 100,000 samples are generated for Monte-Carlo simulations with their estimated PDF also illustrated in Figure 3 and 4 by dashed lines. The probability distribution of excess fuel consumption obtained from the Monte-Carlo simulation is presented in Figure 5 for both AC and PCC pavements.

The results of the Monte-Carlo simulations are used to estimate the sensitivity of roughness-induced excess fuel consumption to input parameter. Figure 6(a) and (b) show the SRCC between roughness-induced excess fuel consumption and three input parameters (IRI, waviness number w, and vehicle speed) for AC and PCC pavements. Positive and negative values of SRCC respectively indicate direct and inverse relationship between input parameters and model outputs. For instance, increasing IRI and reducing the waviness number result in an increase in excess fuel consumption. To compare the

sensitivity of different input parameters, normalized SRCC is illustrated in Figures 6(c) and (d). The SRCC values, their 95% confidence bound and their normalized value are also summarized in Table 3. The sensitivity analysis reveals that roughness-induced excess fuel consumption is less sensitive to variation of vehicle speed, while both IRI and waviness number contribute significantly to the sensitivity of excess fuel consumption. This is not surprising: energy dissipation scales with $\mathrm{E}[\delta\mathcal{E}]\sim V^{w-2}$, so that the impact of speed for the given distribution of waviness number (Fig. 3(b), Tab. 2) is minimized. In return, according to Eq. (9), energy dissipation scales with $\mathrm{E}[\delta\mathcal{E}]\sim\mathrm{E}[IRI]^2$, which explains the sensitivity of the model output w.r.t. variations in IRI. Finally, the sensitivity of the output w.r.t. the waviness number stems from both the velocity term and the amplification of the frequency response function in Eq. (9). The sensitivity of the model response to both IRI and w highlights the importance of two roughness parameters for an accurate determination of roughness-induced excess fuel consumption.

Table 2 Mean and Standard Deviation for IRI and Waviness Number Adapted from Kropac and Mucka (*12*)

Pavement type	Statistic	IRI [mm/m]	w [1]
AC	MEAN	1.320	2.475
	STD	0.541	0.417
PCC	MEAN	1.617	2.479
	STD	0.492	0.314

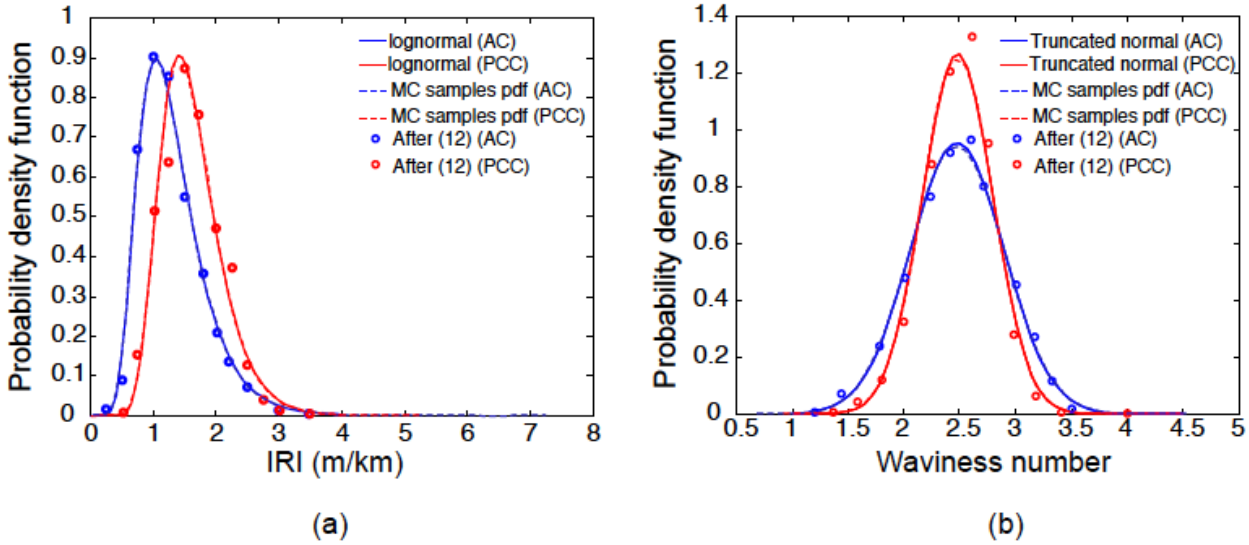


FIGURE 3 Probability distribution function for (a): IRI; (b): waviness number. Dashed lines are the PDF of generated samples for Monte-Carlo simulation.

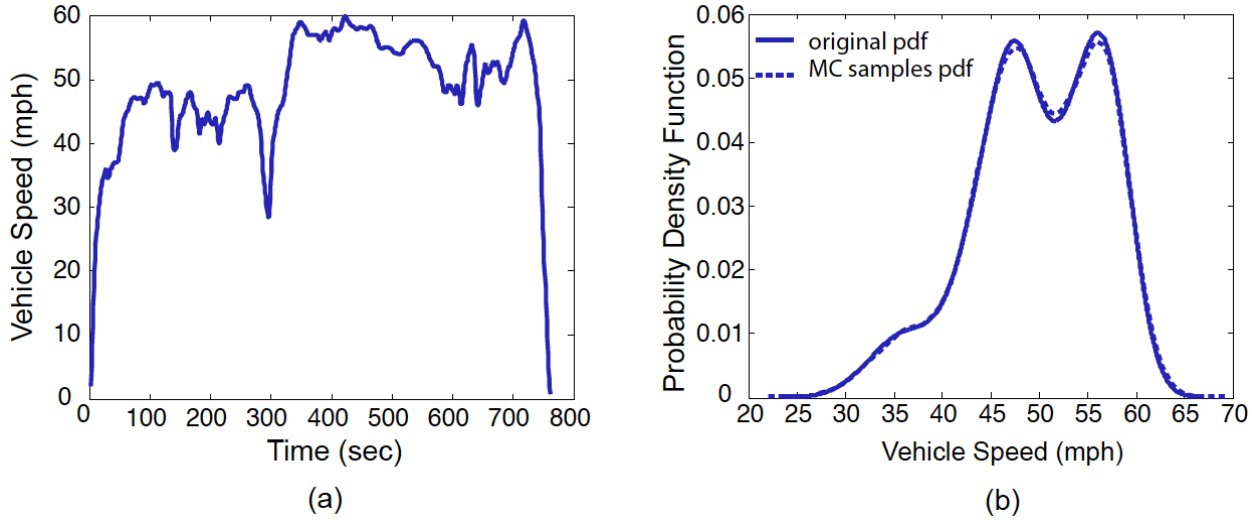


FIGURE 4 Vehicle speed (a): time history from the Highway Fuel Economy Driving Schedule (HWFED) provide by the US EPA (*14*); (b): probability density function evaluated from HWFED and by filtering out stop and go segments. Dashed lines are the PDF of generated samples for Monte-Carlo simulation.

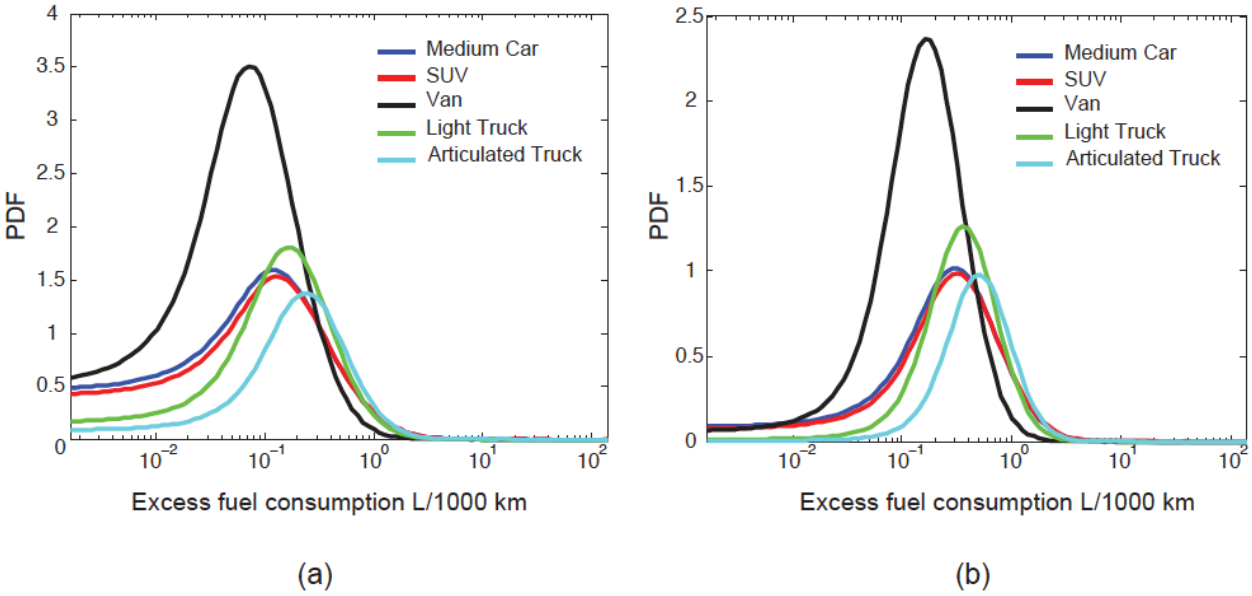


FIGURE 5 Probability distribution of roughness-induced excess fuel consumption for five vehicle classes and for (a): AC pavements; (b): PCC pavements

TABLE 3 Spearman Rank Correlation Coefficient with 95% Confidence Interval

Pavement Type	cars	SRCC			Normalized SRCC %		
		Waviness number	IRI	Speed	Waviness number	IRI	Speed
AC	Medium Car	-0.7243 (-0.7273, -0.7214)	0.6522 (0.6486, 0.6557)	0.0547 (0.0485, 0.0609)	50.61	45.57	3.82
	SUV	-0.7231 (-0.7260, -0.7201)	0.6543 (0.6508, 0.6579)	0.0558 (0.0496, 0.0619)	50.46	45.65	3.89
	VAN	-0.6034 (-0.6073, -0.5994)	0.7664 (0.7638, 0.7690)	0.0645 (0.0584, 0.0707)	42.07	53.43	4.50
	Light Truck	-0.4849 (-0.4897, -0.4802)	0.8492 (0.8474, 0.8509)	0.0712 (0.0650, 0.0773)	34.51	60.43	5.07
	Articulated Truck	-0.3869 (-0.3922, -0.3816)	0.9017 (0.9005, 0.9029)	0.0755 (0.0693, 0.0816)	28.36	66.10	5.53
PCC	Medium Car	-0.7246 (-0.7276, -0.7217)	0.6495 (0.6460, 0.6531)	0.0796 (0.0735, 0.0858)	49.85	44.68	5.48
	SUV	-0.7254 (-0.7283, -0.7225)	0.6494 (0.6458, 0.6530)	0.0803 (0.0741, 0.0864)	49.85	44.63	5.52
	VAN	-0.6093 (-0.6132, -0.6054)	0.7587 (0.7561, 0.7613)	0.0920 (0.0858, 0.0981)	41.73	51.97	6.30
	Light Truck	-0.4889 (-0.4936, -0.4842)	0.8442 (0.8424, 0.8460)	0.1010 (0.0949, 0.1072)	34.09	58.87	7.04
	Articulated Truck	-0.3887 (-0.3939, -0.3834)	0.8985 (0.8973, 0.8997)	0.1066 (0.1005, 0.1128)	27.89	64.46	7.65

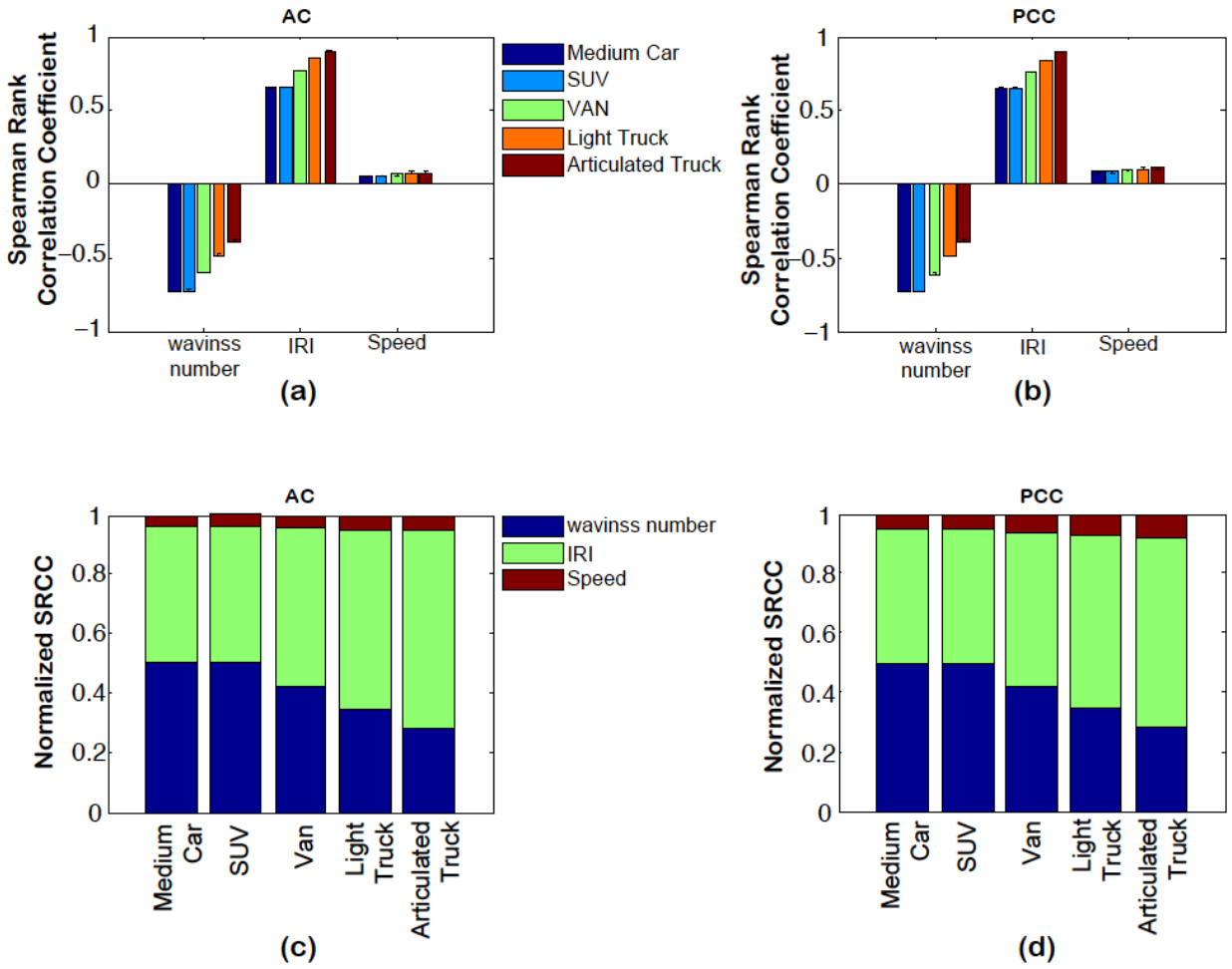


FIGURE 6 Plots of sensitivity of excess fuel consumption to different input parameters. Spearman rank correlation coefficients ρ evaluated for five vehicle classes used in calibrated HDM4 model for (a): AC pavements and (b): PCC pavements. Normalized SRCC as measure of sensitivity for (c): AC pavements and (d): PCC pavements.

APPLICATION OF CALIBRATED ROUGHNESS MODEL WITH LTPP PROFILE DATA

For purpose of illustration, we show how the mechanistic model can be employed when profile data is available. The profile data originate from FHWA's Long-Term Pavement Performance (LTPP) program (*15*), in form of longitudinal profiles along the wheel path for in-service pavements measured over time to evaluate road roughness and its variations. The specific two sections employed are representative of two sections in California (06-9049 and 06-3042).

Employing the model with profile data requires in a first step the determination of the roughness PSD parameters. Assuming that road profiles are ergodic processes, this is achieved by performing a Fourier transformation of the profiles:

$$S_\xi(\Omega) = \lim_{x\to\infty} \mathrm{E}\left[\left|\hat{\xi}(\Omega)\right|^2\right] \quad (12)$$

where $\widehat{(\ )}$ denotes Fourier transform. The PSD parameters (c and w) are estimated by fitting a line to the PSD in log-log space (Figure 7). We also determine the IRI, and the average rectified slope for the golden car traveling with speed 80 km/h, for these profiles via the method described in Ref. (*3*). Figure 8 shows the variation of IRI and waviness number over time for the two considered profiles.

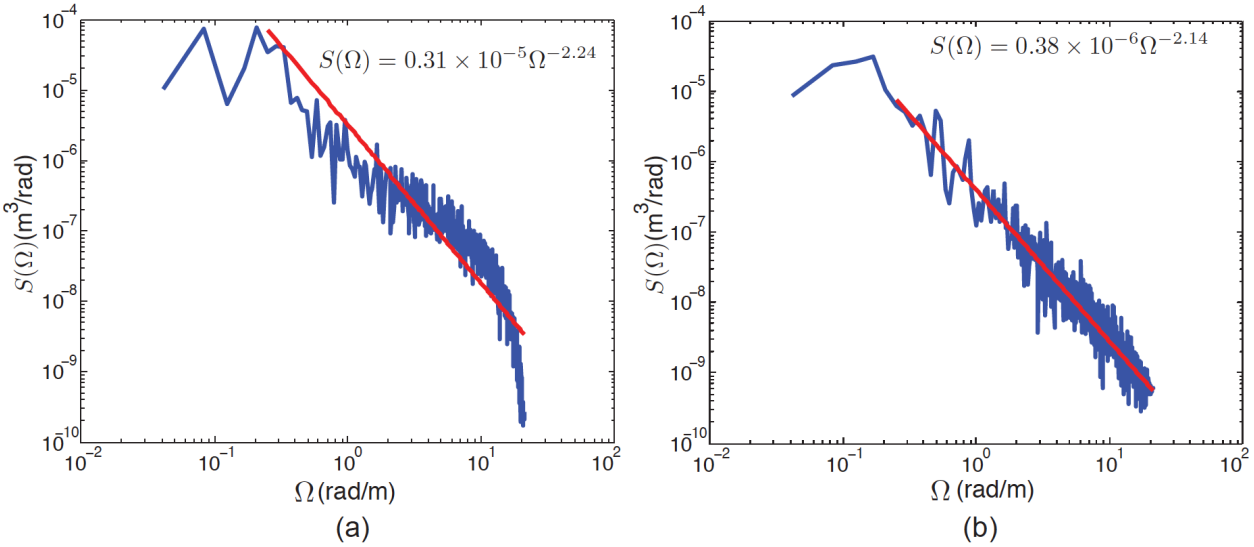


FIGURE 7 Plots of roughness power spectral density for (a): road profile of 06-9049 in 2010 and (b): road profile of 06- 3042 in 2005 both located in California. Red line is the estimated power function for roughness PSD.

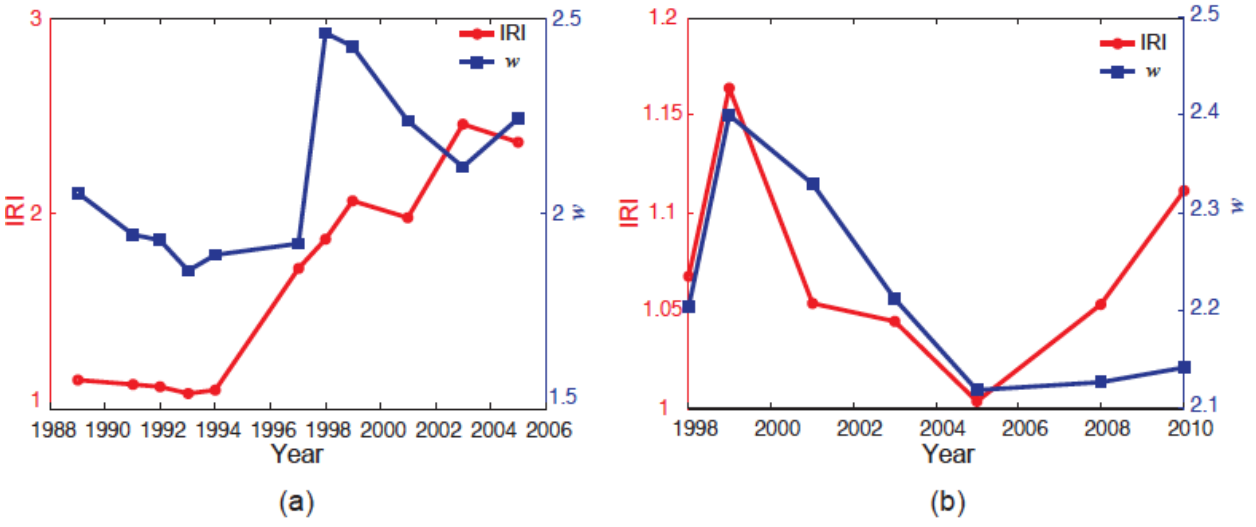


FIGURE 8 Plots of IRI and waviness number over time for (a): road 06-9049 and (b): road 06-3042

With the PSD parameters available, the excess fuel consumption due to pavement roughness is evaluated using both the mechanistic model as defined by Eqn. (9) and (10), and the HDM4 model. The

excess fuel consumption for a medium car and an articulated truck evaluated from the two methods are compared in Figure 9. Comparing the two LTPP sections in Figure 9, section 06-9049 has higher fuel consumption predicted by both methods than section 06-3042 mainly due to significantly higher IRI values. The excess fuel consumption obtained from the HDM4 model has the same trend as IRI. This is inevitable since this model uses only a single index, IRI, for road roughness representation. The mechanistic model results, however, do not exactly follow the variation of IRI, as the excess fuel consumption estimates depend on both IRI and waviness number w. It is also observed that for waviness numbers close to 2 the results from the two methods become very similar.

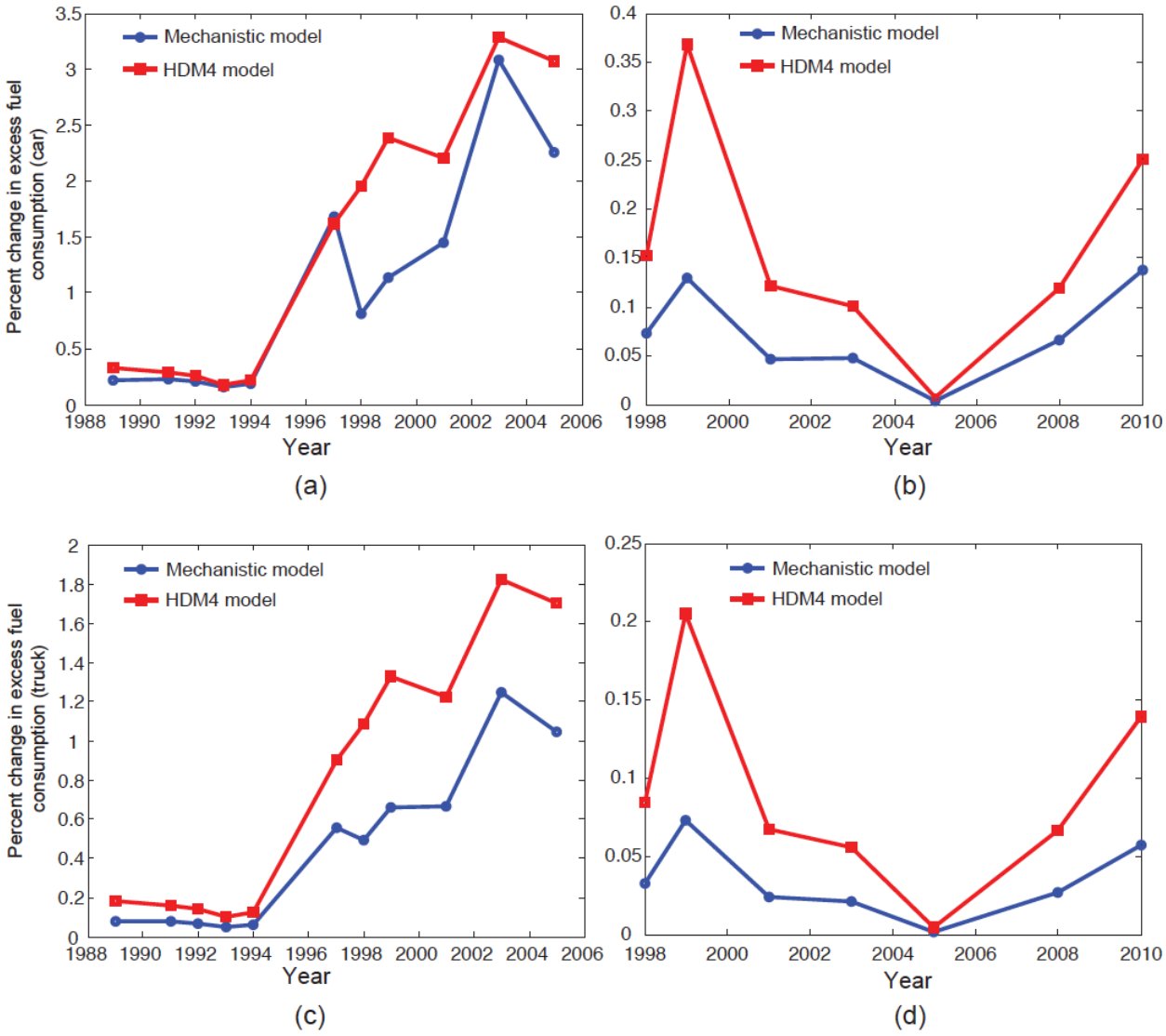


FIGURE 9 Plots of percent change in fuel consumption over time for (a): a medium car traveling on 06-9049; (b): a medium car traveling on 06-3042; (c): an articulated truck traveling on 06-9049 and (d): an articulated truck traveling on 06-3042

CONCLUSIONS

The mechanistic engineering model herein quantifies the impact of pavement surface characteristics on vehicle fuel consumption as one source of energy dissipation related to Pavement Vehicle Interaction; in addition to other sources of energy dissipation related to texture (*16*), and pavement structural and material properties (*17, 18*). Such models are in high demand for evaluating the environmental footprint of pavement structures during their use phase, contributing to the development of a quantitative framework for pavement sustainable design and maintenance.

The distinguished feature of our model is that it combines a thermodynamic quantity (energy dissipation) with results from random vibration theory in order to identify the governing parameters that drive the excess fuel consumption due to pavement roughness:

1. While previous empirical approaches, like the HDM4 model (*5,6*), identified IRI as the key engineering parameter driving roughness-induced excess fuel consumption, our results indicate that (at least) a second road roughness parameter, namely the waviness number w, is required to characterize the impact of pavement surface characteristics on vehicle energy dissipation and fuel consumption. We come to this conclusion from a sensitivity analysis using Spearman rank correlation coefficient method together with FHWA's LTPP database, which shows that the predicted fuel consumption is as sensitive to the waviness number as it is to IRI. As shown in the application of our model to two sections from LTPP database, this waviness number is readily determined from profile data along with IRI.
2. In contrast to linear empirical relationships between IRI, rolling resistance and excess fuel consumption proposed in the HDM4 model, our model forecasts a scaling of energy dissipation with the square of IRI. This is due to the fact that the relative motion in a vehicle's suspension system scales linearly with IRI, whereas the dissipated energy scales with the mean square of suspension motion. That is, all other parameters equal, an increase of IRI by a factor of λ would entail an increase of excess fuel consumption by a factor of λ^2. This scaling is of some importance for e.g. pavement management systems, which often use IRI as a metrics for maintenance decisions.
3. In contrast to other sources of PVI-related excess fuel consumption, which show a high-sensitivity to vehicle speed due to the viscoelastic nature of the pavement (*17,18*), we find that roughness-induced excess fuel consumption is less sensitive to speed. This is due to the fact that the energy dissipation scales with the speed as V^{w-2}, and that waviness numbers of pavements are typically on the order of $w = 2.5 \pm 0.5$ (mean$\pm$ standard deviation in LTPP database). Otherwise said, a distinct speed sensitivity of PVI should not be attributed to roughness, but to other sources of energy dissipation.

In summary, road roughness has been recognized to be a main contributor to vehicle rolling resistance. It is thus necessary to come up with accurate roughness models for vehicle fuel consumption. In this regard, introducing the waviness number, as a second roughness index, in addition to IRI, allows a more accurate quantification of the impact of surface characteristics on vehicle fuel consumption and the corresponding greenhouse gas emission. The new roughness index can be easily evaluated by adding a module to the ProVAL software for implementation purposes.

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