Roughness-Induced Pavement–Vehicle Interactions
Key Parameters and Impact on Vehicle Fuel Consumption

Arghavan Louhghalam, Mehdi Akbarian, and Franz-Joseph Ulm

Pavement roughness affects rolling resistance and thus vehicle fuel consumption. 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 and results in excess fuel consumption. This dissipation depends on both road roughness and vehicle dynamic characteristics. This paper proposes, calibrates, and implements a mechanistic model for roughness-induced dissipation. The distinguishing feature of the model is its combination of a thermodynamic quantity (energy dissipation) with results from random vibration theory to identify the governing parameters that drive the excess fuel consumption caused by pavement roughness, namely, the international roughness index (IRI) and the waviness number, $w$ (a power spectral density parameter). It is shown through sensitivity analysis that the sensitivity of model output, that is, 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 emissions. This aspect is illustrated by application of the roughness–fuel consumption model to two road profiles extracted from FHWA’s Long-Term Pavement Performance database.

It has long been recognized that pavement roughness affects the pavement–vehicle interaction (PVI) and contributes to vehicle operating costs (VOC) (1; ASTM STP 884). The most prominent VOC model is the Highway Developmental Management System, Version 4 (HDM-4) model, which relates a measurable pavement roughness parameter, the international roughness index (IRI) introduced originally for quantifying ride comfort (2, 3), through empirically calibrated vehicle-dependent functional relationships, to fuel consumption (4, 5). Such VOC models have gained importance in the context of engineering life-cycle assessment methods of pavement structures that relate pavement condition to rolling resistance and corresponding fuel consumption and environmental impacts (6). This study identifies the key parameters for roughness-induced fuel consumption.

Roughness-induced fuel consumption is caused by energy dissipation in a 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 should provide a direct means to relate pavement roughness and vehicle-specific physical quantities to fuel consumption. This approach is shown in the first part of the paper. Instead of a single-value roughness index, such as IRI, roughness power spectral density (PSD) is used as a refined means to describe the distribution of roughness across various wavelengths. How this mechanistic model can be calibrated when the HDM-4 model is used is shown. Finally, the novel VOC model is applied with road profiles extracted from FHWA’s Long-Term Pavement Performance (LTPP) database, and the differences in dissipation and fuel consumption between this study’s prediction and the HDM-4 model are discussed.

THEORETICAL BACKGROUND: MECHANISTIC MODEL FOR ROUGHNESS-INDUCED PVI

The first-order evaluation of the energy dissipation by a vehicle’s suspension system considers the classical 2-degrees-of-freedom (df) quarter-car model (Figure 1a), 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 $C_s$) (7). The dissipation of mechanical work into heat form is caused by the relative motion, $\dot{z} = dz/dt$ (where $z$ is the relative displacement of sprung mass $m_s$ with respect to the unsprung mass $m_u$) of the suspension system, that is, $\dot{\delta}D = C_s \dot{z}$, expressed as the expected value of energy dissipated per traveled length at constant speed $V$:

$$E[\delta t] = \frac{C_s}{V} E[z^2]$$

(1)

The suspension motion $\dot{z} = dz/dt$ is caused by road roughness transmitted from the ground by tire stiffness $k_t$. It is generally assumed that road roughness $\xi$ is a zero-mean stationary Gaussian process (8). In practice, the power spectral density of road profile is represented as a power function of the angular wave number, $\Omega$ (9):

$$S_\delta(\Omega) = c \Omega^w$$

(2)

where the unevenness index, $c$, and the waviness number, $w$, characterize the road profile. Equation 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 use of random vibration theory to link the mean square of suspension

A. Louhghalam, Room 1-382; M. Akbarian, Room E39; and F.-J. Ulm, Room 1-263, Department of Civil and Environmental Engineering, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139. Corresponding author: F.-J. Ulm, ulm@mit.edu.
motion in Equation 1 to both dynamic properties of the vehicle and roughness parameters (10): 

\[
E[\dot{\delta}^2] = \int_0^\infty V^2 \Omega^2 |H_s(V\Omega)|^2 \mathcal{S}_\xi(\Omega) d\Omega
\]  

(3)

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

\[
H_s(\omega) = \frac{\omega^2 k_m}{(\alpha m \omega^2 + i C_s \omega + k_s)\omega^2 + (i C_s \omega + k_s)^2}
\]  

(4)

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

Thus, with Equations 1 and 3 combined, 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 characteristics through roughness PSD parameters (i.e., waviness number \(w\) and the unevenness index \(c\)) as well as vehicle properties by FRS:

\[
E[\dot{\delta}^2] = c C_s V^2 \int_0^\infty \Omega^2 \omega^2 |H_s(V\Omega)|^2 d\Omega
\]  

(5)

or for the circular frequency:

\[
E[\dot{\delta}^2] = c C_s V^2 \int_0^{\infty} \omega^2 |H_s(\omega)|^2 d\omega
\]  

(6)

The argument inside the integral of Equation 6 does not depend on vehicle speed, and the energy dissipation is found to scale with the vehicle speed as \(E[\dot{\delta}^2] \sim V^{w-2}\). That is, for waviness numbers \(w > 2\), the roughness-induced dissipated energy increases with the speed, and for \(w < 2\) it is the inverse. This scaling is used later in applications.

At this stage of the development, it is appropriate to close the loop with other roughness-induced VOC models based on the IRI, such as the HDM-4 model (4, 5) for vehicle fuel consumption and related greenhouse gas (GHG) emissions. Recall 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):

\[
\text{IRI} = \frac{1}{V_0 L} \int_0^L |v_{10}| dx
\]  

(7)

where the subscript GC denotes the golden-car properties, given in Figure 1b. Assuming the road profiles are stationary Gaussian processes, the expected value of IRI can be written as roughness PSD parameters in the form of (10)

\[
E[\text{IRI}] = \sqrt{\frac{2}{\pi}} V_0^{-w-2} \int_0^{\infty} \omega^{w-2} |H_{s,GC}(\omega)|^2 d\omega
\]  

(8)

where \(H_{s,GC}\) is the FRS of the golden car. A final substitution of Equation 8 into Equation 6 provides the following expression for the energy dissipation:

\[
E[\dot{\delta}_c] = \frac{\pi}{2} C_s V_0 \left( \frac{V}{V_0} \right)^{w-2} \times \frac{\int_0^{\infty} \omega^{w-2} |H_s(\omega)|^2 d\omega}{\int_0^{\infty} \omega^{w-2} |H_{s,GC}(\omega)|^2 d\omega} \times E[\text{IRI}]
\]  

(9)

Expression 9 contributes to a full appreciation of the added value of the mechanistic-based roughness-induced PVI model compared with other empirical models. Specifically, the dissipated energy scales with the square of (the expected value) of IRI and 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, as shown in what follows.

**CALIBRATION WITH HDM-4 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-df system as a quarter-vehicle model. In reality the dynamic behavior of vehicles is far more complicated than can be comprehensively captured by a single quarter-car model. Although 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, because the total stiffness involved in various components of a vehicle is much more complex than suspension and tire stiffness.

As an alternative, and in the absence of such detailed measurements, here the HDM-4 model is used to calibrate the mechanistic roughness-induced PVI model (4, 5). Such a calibration is made to determine the stiffness properties for the various vehicle classes, together with the road waviness number as an additional adjustable parameter. In the HDM-4 model, the variation of excess fuel consumption caused by a unit change in IRI is reported for various driving speeds and for vehicle classes: medium car, sport utility vehicle (SUV), van, light truck, and articulated truck. The properties of these vehicles, obtained from literature, are summarized in Table 1 (11–13). To calibrate the model, total fuel consumption evaluated from the HDM-4 model at reference IRI = 1 m/km is used as the baseline, \(\text{IFC}_0 = \text{IFC}(\text{IRI}_0)\), where \(\text{IFC}\) is instantaneous fuel consumption, and roughness-induced dissipated energy evaluated from Equation 9 is converted to excess fuel consumption with an engine efficiency coefficient (\(\eta_0\) in milliliters per kilowatt per second, given for the vehicle classes in Table 1):

\[
E[\delta \text{IFC}] = \eta_0 E[\dot{\delta}_c]
\]  

(10)
The percentage change in fuel consumption caused by the change in IRI relative to reference IRI 0 with the mechanistic model is evaluated as follows:

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

The corresponding data points IFC(IRI, V)/IFC 0 −1 from calibrated HDM-4 model are obtained for IRI values varying from 1 to 6 m/km and vehicle speeds of 56 to 112 km/h associated with the range of vehicle speed in field measurements (4). 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

$$\beta = \sqrt{\frac{k_m}{k_m}}$$

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 the form of plots of the total fuel consumption versus IRI, comparing the results with the predictions of the HDM-4 model (4). Unlike the HDM-4 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 Equation 9 and Figure 2. The fitted dimensionless coefficients β 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 FHWA LTPP program reported by Kropac and Mucka (14), which exhibits a mode at around w = 2.5. This agreement is an independent validation of the presented modeling approach of roughness-induced PVI.

**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 with respect to the uncertainty in model input parameters. Such a sensitivity analysis identifies the main factors driving the uncertainty of model output and quantifies the associated contribution. Here, the Spearman rank correlation coefficient (SRCC) is used to determine the sensitivity of the energy dissipation to input parameters of the roughness model (15). 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

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**TABLE 1  Vehicle Dynamical Properties per Axle**

| Car Class Property | Medium Car | SUV | Van | Light Truck | Articulated Truck |
|--------------------|------------|-----|-----|-------------|------------------|
| m̅ (tons)           | 1.46 (3)   | 2.5 (3) | 2.54 (3) | 6.5 (3) | 34.9 (2)         |
| m̅ (kg)             | 80 (11)    | 125 (3) | 134 (12) | 395 (b) | 544 (13)         |
| k (kN/m)           | 29.44 (11) | 189 (a) | 48 (a)   | 337 (b) | 700 (13)         |
| ξ̅           | 0.096 (3)  | 0.072 (3) | 0.072 (3) | 0.062 (3) | 0.059 (3)       |
| β                | 46.98      | 28.03 | 31.00 | 14.90 | 13.30             |

Note: Reference numbers given in parentheses.

a CARSIM software template.
b GMC specification.

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(continued)
variables across the entire design space and accounts for the interaction between input parameters. Monte Carlo simulations are performed by generating realizations of input parameters according to their distribution in the roadway network. The roughness mechanistic model in Equation 9 for each realization is used to evaluate roughness-induced dissipation and relevant fuel consumption. This result is then used to evaluate SRCC between each input parameter and the excess fuel consumption.

**MONTE CARLO SIMULATION**

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

For the distribution of IRI and waviness number, the results of the empirical distributions of the LTPP program of the FHWA data set reported by Kropac and Mucka is used (14). 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 PDF for vehicle speed is evaluated from the highway fuel economy driving schedule (HWFED) provided by the U.S. Environmental Protection Agency, which represents highway driving conditions for vehicles traveling below 60 mph (16). Because the presented model is developed with the steady state assumption for constant vehicle speed, the vehicle speeds associated with the stop-and-go condition, that is, speeds lower than 30 mph at the beginning and the end of speed time history, are filtered out for PDF estimation (Figure 4).

To generate a random number with cumulative distribution function \( F_X(x) \), the inverse transformation technique is used. 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 cumulative distribution function \( F_X(x) \). The technique is used here to generate random variables from parametric distributions shown in Figure 3 (lognormal for IRI and waviness number), as well as the nonparametric empirical PDF illustrated in Figure 4b for vehicle speed. A total of 100,000 samples are generated for Monte Carlo simulations with their estimated PDF also illustrated in Figures 3 and 4 by dashed lines. The probability distribution of excess fuel consumption obtained
TABLE 2  Mean and Standard Deviation for IRI and Waviness Number (14)

| Pavement Type | Statistic | IRI (mm/m) | w (1) |
|---------------|-----------|------------|-------|
| AC            | Mean      | 1.320      | 2.475 |
|               | Standard deviation | 0.541      | 0.417 |
| PCC           | Mean      | 1.617      | 2.479 |
|               | Standard deviation | 0.492      | 0.314 |

Note: AC = asphalt concrete; PCC = portland cement concrete.

from the Monte Carlo simulation is presented in Figure 5 for both asphalt concrete (AC) and portland cement concrete (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, shows 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 a 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. Comparing the sensitivity of various input parameters, normalized SRCC is illustrated in Figure 6, c and d. The SRCC values, their 95% confidence limits, and their normalized value are 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 $E[\delta \varepsilon] \sim V^{-2}$, so that the impact of speed for the given distribution of waviness number (Figure 3b, Table 2) is minimized. In return, according to Equation 9, energy dissipation scales with $E[\delta \varepsilon] \sim E[\text{IRI}]^2$, which explains the sensitivity of the model output with respect to variations in IRI. Finally, the sensitivity of the output with respect to the waviness number stems from both the velocity term and the amplification of the frequency response function in Equation 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.

FIGURE 3  Probability distribution function for (a) IRI and (b) waviness number (dashed lines = PDF of generated samples for Monte Carlo (MC) simulation).

FIGURE 4  Vehicle speed: (a) time history from HWFED and (b) PDF evaluated from HWFED and by filtering out stop-and-go segments (dashed lines = 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 and (b) PCC pavements.

FIGURE 6  Sensitivity of excess fuel consumption to various input parameters. SRCC $\rho$ evaluated for five vehicle classes used in calibrated HDM-4 model for (a) AC pavements and (b) PCC pavements; normalized SRCC as measure of sensitivity for (c) AC pavements and (d) PCC pavements.
This section shows how the mechanistic model can be used when profile data are available. The profile data originate from FHWA’s LTPP program (17) in the form of longitudinal profiles along the wheelpath for in-service pavements measured over time to evaluate road roughness and its variations. The specific two sections used are representative of two sections in California (06-9049 and 06-3042).

Use of the model with profile data requires in a first step the determination of the roughness PSD parameters, which is done, assuming that road profiles are ergodic processes, by performing a Fourier transformation of the profiles:

\[ S_x(\Omega) = \lim_{\xi \to \infty} E[|\xi(\Omega)|^2] \]

where \( \langle \rangle \) denotes the Fourier transform. The PSD parameters \((c\) and \(w)\) are estimated by fitting a line to the PSD in log-log space (Figure 7). The IRI and the average rectified slope for the golden car traveling at 80 km/h are determined for these profiles with the method described by Sayers (2). Figure 8 shows the variation of IRI and waviness number over time for the two considered profiles.

With the PSD parameters available, the excess fuel consumption caused by pavement roughness is evaluated with both the mechanistic model as defined by Equations 9 and 10 and the HDM-4 model.

| Pavement Type | Vehicle | Waviness Number | IRI   | Speed | Normalized SRCC (%) |
|---------------|---------|-----------------|-------|-------|---------------------|
|               |         |                 |       |       | Waviness Number | IRI | Speed |
| AC            | Medium car | -0.7243 | 0.6522 | 0.0547 | 50.61 | 45.57 | 3.82 |
|               | SUV     | -0.7251 | 0.6543 | 0.0558 | 50.46 | 45.65 | 3.89 |
|               | Van     | -0.6034 | 0.7664 | 0.0645 | 42.07 | 53.43 | 4.50 |
|               | Light truck | -0.4849 | 0.8492 | 0.0712 | 34.51 | 60.43 | 5.07 |
|               | Articulated truck | -0.3869 | 0.9017 | 0.0755 | 28.36 | 66.10 | 5.53 |
| PCC           | Medium car | -0.7246 | 0.6495 | 0.0796 | 49.85 | 44.68 | 5.48 |
|               | SUV     | -0.7254 | 0.6494 | 0.0803 | 49.85 | 44.63 | 5.52 |
|               | Van     | -0.6093 | 0.7587 | 0.0920 | 41.73 | 51.97 | 6.30 |
|               | Light truck | -0.4889 | 0.8442 | 0.1000 | 34.09 | 58.87 | 7.04 |
|               | Articulated truck | -0.3887 | 0.8985 | 0.1006 | 27.89 | 64.46 | 7.65 |

Note: 95% confidence limits given in parentheses.

### TABLE 3 Spearman Rank Correlation Coefficient with 95% Confidence Interval

| Pavement Type | Vehicle | Waviness Number | IRI   | Speed | Normalized SRCC (%) |
|---------------|---------|-----------------|-------|-------|---------------------|
|               |         |                 |       |       | Waviness Number | IRI | Speed |
| AC            | Medium car | -0.7243 | 0.6522 | 0.0547 | 50.61 | 45.57 | 3.82 |
|               | SUV     | -0.7251 | 0.6543 | 0.0558 | 50.46 | 45.65 | 3.89 |
|               | Van     | -0.6034 | 0.7664 | 0.0645 | 42.07 | 53.43 | 4.50 |
|               | Light truck | -0.4849 | 0.8492 | 0.0712 | 34.51 | 60.43 | 5.07 |
|               | Articulated truck | -0.3869 | 0.9017 | 0.0755 | 28.36 | 66.10 | 5.53 |
| PCC           | Medium car | -0.7246 | 0.6495 | 0.0796 | 49.85 | 44.68 | 5.48 |
|               | SUV     | -0.7254 | 0.6494 | 0.0803 | 49.85 | 44.63 | 5.52 |
|               | Van     | -0.6093 | 0.7587 | 0.0920 | 41.73 | 51.97 | 6.30 |
|               | Light truck | -0.4889 | 0.8442 | 0.1000 | 34.09 | 58.87 | 7.04 |
|               | Articulated truck | -0.3887 | 0.8985 | 0.1006 | 27.89 | 64.46 | 7.65 |

Note: 95% confidence limits given in parentheses.
has the same trend as IRI, which is inevitable because 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 \( w \). For waviness numbers close to 2, the results from the two methods become very similar.

CONCLUSIONS

The mechanistic engineering model given here quantifies the impact of pavement surface characteristics on vehicle fuel consumption as one source of energy dissipation related to PVI, in addition to other sources of energy dissipation related to texture (18) and pavement structural...
and material properties (19, 20). 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 distinguishing feature of the presented model is that it combines a thermodynamic quantity (energy dissipation) with results from random vibration theory for identifying the governing parameters that drive excess fuel consumption caused by pavement roughness:

1. Previous empirical approaches, such as the HDM-4 model (4, 5), identified IRI as the key engineering parameter driving roughness-induced excess fuel consumption. However, the results here indicate that (at least) a second road roughness parameter, the waviness number, \( w \), is needed to characterize the impact of pavement surface characteristics on vehicle energy dissipation and fuel consumption. This conclusion was reached through a sensitivity analysis using the SRCC 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 by the application of the model to two sections from the LTPP database, this waviness number is readily determined from profile data along with IRI.

2. In contrast to linear empirical relationships between IRI, rolling, and excess fuel consumption proposed in the HDM-4 model, the presented model forecasts a scaling of energy dissipation with the square of IRI, because 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 being equal, an increase of IRI by a factor of \( \lambda \) would entail an increase of excess fuel consumption by a factor of \( \lambda^2 \). This scaling is of importance, for example, for pavement management systems, which often use IRI as metrics for maintenance decisions.

3. In contrast with other sources of PVI-related excess fuel consumption, which show a high sensitivity to vehicle speed because of the viscoelastic nature of the pavement (19, 20), roughness-induced excess fuel consumption is less sensitive to speed, because the energy dissipation scales with the speed as \( V_w \), and waviness numbers of pavements typically are on the order of \( w = 2.5 \pm 0.5 \) (mean ± standard deviation in the LTPP database). In other words, a distinct speed sensitivity of PVI should be attributed not to roughness but to other sources of energy dissipation.

Road roughness has been recognized as a main contributor to vehicle rolling resistance. Thus accurate roughness models for vehicle fuel consumption are needed. Introducing the waviness number, as a second roughness index in addition to IRI, allows more accurate quantification of the impact of surface characteristics on vehicle fuel consumption and the corresponding GHG emissions. The new roughness index can be evaluated easily by adding a module to the ProVAL software for implementation.

ACKNOWLEDGMENTS

This research was carried out by the Massachusetts Institute of Technology Concrete Sustainability Hub with sponsorship from the Portland Cement Association and the Ready Mixed Concrete Research and Education Foundation.

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