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Sensitivity analysis of a deflection-induced pavement–vehicle interaction model

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Different models have been developed to quantify the energy dissipation in pavements due to pavement–vehicle interaction (PVI). The present study focuses on a mechanistic model for estimating deflection-induced excess fuel consumption (EFC). Due to the non-linearity of the models, the calculated dissipation is dependent on the resolution and accuracy of input data. A comprehensive sensitivity analysis was thus conducted to evaluate the sensitivity of the model's EFC calculations to the use of average hypothetical data versus real traffic recorded inputs. In addition, the pavement deterioration and reduction of mechanical performance during the service life were considered as potential factors to affect predictions on deflection-induced EFC. Results showed that depending on the resolution of some parameters (i.e. temperature and traffic congestion), the estimated EFC due to PVI was greatly affected. Network-level analyses should thus be calibrated, clearly identifying the resolution of input parameters into the models.

Keywords: pavement–vehicle interaction; excess fuel consumption; rolling resistance; road pavements; sensitivity analysis

Introduction

Rolling resistance due to pavement design and condition is important because it affects the fuel consumption of the vehicles driving on the pavements, which has significant economic and environmental consequences (Akbarian, Moeini-Ardakani, Ulm, & Nazzal, 2012). Rolling resistance is mainly due to three dissipative pavement–vehicle interaction (PVI) mechanisms: pavement deflection, roughness, and texture. Deflection-induced PVI results in the dissipation of energy due to the viscoelasticity of the pavement material, while pavement roughness and texture lead to energy consumption in the suspension system and tyre of vehicles, respectively. As the dissipated energy must be compensated with excess engine power, these mechanisms result in excess fuel consumption (EFC) and its associated greenhouse gas and air pollution emissions. This study focuses only on deflection-induced PVI, however, both texture and roughness affect the fuel consumption and studying their impacts on fuel consumption is the focus of ongoing research of the authors and others.

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Experiments have been conducted to quantify the impacts of rolling resistance on EFC (Hultqvist, 2008, 2013; Taylor, 2002; Taylor & Patten, 2006; Zaabar & Chatti, 2011). A limitation of these empirical approaches is that they are only relevant to the specific experimental conditions in which the tests were conducted, including climate and pavement design. As such, several mechanistic models have been developed to quantify the dissipated energy due to rolling resistance and the associated EFC (Bester, 1981; Biggs, 1988; Zaabar & Chatti, 2010; Pouget, Sauzéat, Benedetto, & Olard, 2012; Louhghalam, Akbarian, & Ulm, 2014b; Coleri & Harvey, 2013; Zaabar & Chatti, 2014; Louhghalam, Tootkaboni, & Ulm, 2015). These models are mathematical tools whose main goal is to predict the energy dissipation rate of a vehicle moving on a pavement. The dissipation rate is then related to EFC by means of conversion factors (U.S. Department of Energy, 2000; U.S. Energy Information Administration, 2013).

Most of the PVI models have only been applied to a limited number of general cases, so it is hard to know how sensitive they are to particular assumptions such as changes in traffic flow during peak/off-peak hours, or hourly variations in pavement temperature compared to average daily temperature, or the combined effects of both parameters. Because the models are not linear, considering average values as inputs could lead to approximations. Therefore, the accuracy of the model depends on the resolution of input parameters. For example, pavement deflection is related to stiffness, which is in turn affected by pavement temperature. Considering the average annual temperature, the average monthly temperature, the average daily temperature, or even the average hourly temperature can affect the overall results in terms of deflection-induced extra-fuel consumption and, finally, carbon equivalent emissions. Similarly, traffic is not constant throughout the average annual day but mostly flows during peak hours causing greater extra-fuel consumption on specific hours of the day. On those particular hours, speed, which also affects greatly the PVI models, is far from being constant and commonly varies according to the traffic stream density (Transportation Research Board, 2016). Coupling temperature information with traffic flow, or speed, at different scales and level of detail, may lead to a possible superposition of effects and consequent underestimation or overestimation of EFC.

Furthermore, roadways deteriorate during their service life, and pavement deflection under moving loads is thus going to change due to cracking and subgrade loss of support, for instance. Lower stiffness is consequently expected with increasing time unless maintenance activities are being conducted on the road. Accordingly, maintenance strategies have the potential to affect dramatically the EFC predictions of vehicles running on a well-maintained roads respect to poor and deteriorated routes (Louhghalam, Akbarian, & Ulm, 2017). Current PVI models assume that the road maintains its performance as a new pavement and disregard continuous pavement degradation during the service life. EFC can, therefore, be underestimated or overestimated depending on the specific assumptions of the model. There is clearly a significant opportunity to conduct sensitivity analyses of input parameters for these PVI models.

Most of mechanistic pavement-vehicle interaction models are computationally demanding and involve large transient finite element analysis. In this study, we focus on the deflection-induced PVI model developed by Louhghalam, Akbarian, and Ulm (2014a) because the model is fast and efficient and allows for network scale analysis. Thus, in this paper we examine the sensitivity of the fuel consumption estimations by this model to the resolution of the network-level available data. The model is previously calibrated and validated in (Louhghalam et al., 2014b) and is used here to evaluate the sensitivity of the model's EFC calculations due to the resolution of specific parameters (e.g. average annual temperature values vs. hourly temperature values). Furthermore, the sensitivity of the fuel consumption to long-term pavement deterioration is investigated.

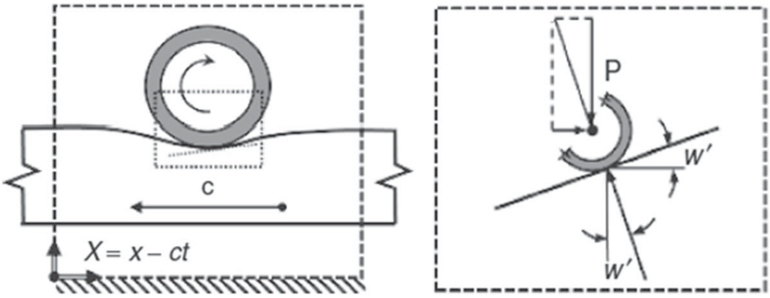

Figure 1. (a) Pavement-vehicle interaction in moving coordinate system. (b) Magnified detail of the slope under the wheel (from Louhghalam et al. 2014a).

Methodology

This section briefly describes the PVI model adopted in the present research, followed by a description of the parameter and deterioration sensitivity analyses. The contribution of each parameter assumption was estimated separately, at first, and then combined to analyse possible superposition effects. This enabled an assessment of the parameter (or combination of parameters) having the greatest impact on EFC.

Deflection-induced PVI model

The model (Louhghalam et al., 2014a) considers a pavement subjected to a load P moving at constant speed c in the x-direction (Figure 1). Due to deformation of the viscoelastic material, energy is irreversibly dissipated, which must be supplied by the engine to make the vehicle advance. This leads to EFC of the vehicle. The energy dissipation rate D is evaluated in a moving coordinate system that is attached to the wheel and moves at speed c. Assuming a steady-state condition under a constant speed c, the dissipation rate D can be written as in equation 1, where the moving coordinate is $X = x - ct$ and x and t are space and time variables, respectively.

$$D = P\frac{\mathrm{d}w}{\mathrm{d}x} = -cP\frac{\mathrm{d}x}{\mathrm{d}X} \geq 0. \tag{1}$$

The non-negativity of the dissipation rate requires that $\mathrm{d}w/\mathrm{d}X < 0$. Due to viscous deformation that occurs (affected by temperature and speed), the load is applied to an upward surface and it leads to an excess in fuel consumption, as fully explained in (Louhghalam et al., 2014a).

The pavement is modelled as a viscoelastic beam on a Winkler foundation and the scaling relationship between energy dissipation and the involved parameters is obtained. The dissipated energy $\delta\epsilon$ was found to be proportional to the square of applied load and inversely proportional to the vehicle speed, similar to the HDM-4 model (Zaabar & Chatti, 2010). Once the dissipated energy is evaluated, it is converted to EFC through a conversion parameter α that represents the energy content per volume of gasoline (U.S. Department of Energy, 2000).

$$\mathrm{EFC} = \alpha \cdot \delta\varepsilon. \tag{2}$$

Finally, the EFC will be converted into equivalent CO_2 emissions (U.S. Energy Information Administration, 2013).

$$\mathrm{CO}_{2eq} = \beta \cdot \mathrm{EFC}, \tag{3}$$

where β is the greenhouse gas emission factor for burning fuel in an engine.

Parameter sensitivity analysis

This sensitivity analysis focuses on three parameters of the deflection-induced PVI model: axial loads, temperature, and speed. Data from the Arizona Department of Transportation were used in this analysis (AZ DOT, 2016; The University of Arizona, 2016) to estimate the sensitivity of the EFC to these parameters.

Deflection-induced dissipation $\delta\epsilon$ in the model (Louhghalam et al., 2014a) scales with the square power of the axial load P. However, the model takes into account the axial load as identified by either a car or HS20-44 truck, the conventional semi- or tractor-trailer vehicle with a 20-ton tractor and 16-ton rear axle. In the model's calculations, light vehicle passages are thus represented by car-induced deflections while HS20-44 trucks identify the entire heavy vehicle fleet.

To find the real axle load in the network of Arizona, weight-in-motion (WIM) data were collected from AZDOT Management System (2016) and the approximations in deflection-induced dissipations due to axial load variation were computed. Gathering WIM data is not an easy task. For this purpose, equivalent factors were also evaluated to convert the EFC caused by a generic axle to the one caused by the equivalent single axle load (ESAL).

Temperature modifies the relaxation properties of viscoelastic pavement materials (i.e. asphalt) and, therefore, deflections, which ultimately affect EFC. The model typically uses the annual average daily temperature, although air and pavement temperatures can be also determined on hourly, daily, weekly, and monthly basis. To evaluate the effect of temperature variations on average daily temperature values, different resolution temperature data were collected from the Arizona Meteorological Network (The University of Arizona, 2016) and the approximations in calculating EFC due to temperature variations were identified.

Energy dissipation and fuel consumption decrease with increasing speed since viscoelastic materials provide a stiffer mechanical response at high loading frequencies. Speed is approximated by the road speed limit in the model. Although this approximation is commonly accepted due to problems in recording real-time vehicle speed, several road sections are equipped with traffic monitoring systems able to capture vehicle speed. In reality, vehicle speed depends on the road occupation. For example, if the road section is approaching saturation, speed is a function of vehicle interactions. Otherwise, if traffic is in a free-flow condition, the vehicle speed is mostly influenced by drivers' behaviour. In order to estimate the impact of such approximations, EFC was evaluated with higher resolution hourly recorded speed as an input parameter.

Fifty road sections of Arizona road network were considered in the analysis. The following conditions were tested to estimate the sensitivity of predictions on EFC. Table 1 summarises the original level of detail (resolution) included in the model and the refined level of detail as tested in the sensitivity analysis. Individual and superposed combinations of temperature, traffic flow, and speed resolution effects on the estimation of EFC are presented.

Deterioration sensitivity analysis

Aging of pavement infrastructure, due primarily to traffic loadings and climate, leads to the deterioration of the stiffness and surface roughness. Damage is accumulated within the pavement and stiffness is thus reduced until specific maintenance interventions are carried out; otherwise, the pavement will fail. The rate of decrease in pavement stiffness is a function of several parameters such as traffic level, traffic spectrum, layer thickness, and material types. If the entire pavement's life cycle is considered in an analysis, then deflection-induced EFC as predicted by PVI models should be taken into account accordingly.

Due to greater availability of data for asphalt sections, the deterioration sensitivity analysis is related to asphalt pavements. The study aims to evaluate the order of magnitude of the changes

Table 1. Parameter sensitivity analysis scope.

Input variable	Original level of detail	Refined level of detail	Source
Axial load configuration	Standard HS20-44 truck and car-like vehicles	Recorded vehicle weight (WIM data)	AZ Transportation Management Systems (AZ DOT, 2016)
Temperature	Annual average	Monthly average	AZ Meteorological Network (The University of Arizona, 2016)
Temperature	Annual average	Weekly average	
Temperature	Annual average	Daily average	
Temperature	Annual average	Hourly average	
Speed	Speed limit	Actual recorded speed	AZ Transportation Management Systems (AZ DOT, 2016)
Traffic volume	AADT/AADTT	Actual recorded traffic flow	AZ Transportation Management Systems (AZ DOT, 2016)

Table 2. PVI approximations on long-term analyses.

Road class	Cumulated traffic in 20 years [ESAL]	Speed limit [km/h]
A	48,690,000	130
B	16,119,000	110
C	7,718,000	90
D	5,443,000	70
E	3,290,000	50

in deflection-induced EFC during pavement life cycle under different traffic levels. Cumulative EFC and the impact of maintenance are evaluated by means of calculating the reduction of EFC due to pavement deterioration compared to a "do-nothing" strategy (i.e. no maintenance) during the pavement service life.

For the purpose of the analysis, the traffic levels in Table 2 were defined as to represent different road classes. Class A traffic represents main roads with high-traffic levels, while class E traffic represents secondary roads with minimal traffic. The speed limit was set as to range between 50 km/h (class E road) to 130 km/h (class A road), while the temperature was kept constant and equal to 25°C. The initial asphalt stiffness was 5000 MPa and a logarithmic deterioration law was assumed as defined by (Collop & Cebon, 1995) depending on traffic. The stiffness at the end of the pavement life (20 years) was 50% of initial stiffness (failure design threshold).

Parameter sensitivity analysis results

Axial load configuration

Since deflection-induced EFC varies with the square of the axial load (P^2), oversimplifying the actual load configurations could potentially result in errors when calculating EFC. WIM data

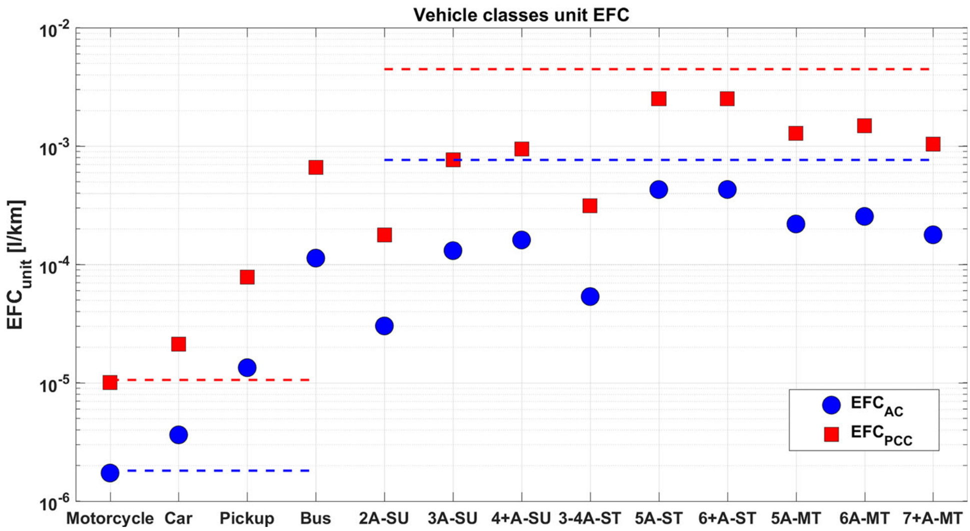

Figure 2. EFC values for higher resolution data for axial load configuration (FHWA classifications listed on x-axis and blue circles for PCC and red squares for AC) and for simplified classifications (blue dashed lines for PCC and red dashed lines for AC) (colour online only).

gathered from AZ DOT (2016) for over 50 segments were analysed and the PVI model was employed with different weights. Dashed horizontal lines in Figure 2 are the simplified EFC of medium car (bottom left) and HS20-44 trucks (upper right). The single dots and squares represent the EFC of FHWA vehicle classifications (2014). EFC values were calculated using actual recorded WIM data for both asphalt concrete (AC – red dots and lines) and Portland cement concrete pavements (PCC – blue dots and lines), respectively. As observed, the assumption of a simplified traffic spectrum by only using two classes of vehicles (cars and HS20-44 trucks) leads to values of EFC that are generally lower than EFC calculated by higher resolution data for light vehicles and higher in the case of heavy vehicles.

Underestimation of the simplified value for car-like vehicles is due to the increased mass of buses and pickups with respect to cars, which are included in the light vehicles classification. For the heavy vehicles, overestimation of the simplified value for trucks is due to the assumption that the HS20-44 truck weight is similar to the maximum allowable gross vehicle weight of 36,000 kg (80,000 lb), while recorded data suggest that there are trucks travelling partially empty. The approximation is even higher if the number of axles of the trucks increases. The maximum allowable weight is spread, in fact, over a higher number of axles and, therefore, the axial load decreases. In addition, the overestimation made on heavy vehicles appears to be more relevant than the underestimation made on light vehicles because of the different order of magnitude of the EFC considered. The approximation caused by the simplified assumption about axial loads is, therefore, expected to overestimate the overall EFC since heavy vehicle contribution appears to be dominant.

Figure 3 confirms this deduction and shows that the approximation scales with the square power of the variation of the axial load. ΔP is defined as:

$$\Delta P[\%] = 100(P_{\mathrm{WIM}} - P_{\mathrm{2CL}})/P_{\mathrm{2CL}}, \tag{4}$$

where P_{WIM} is the averaged axial load evaluated with WIM recorded data and P_{2CL} is the averaged axial load evaluated according to the simplified traffic spectrum (2 classes). ΔEFC (y-axis)

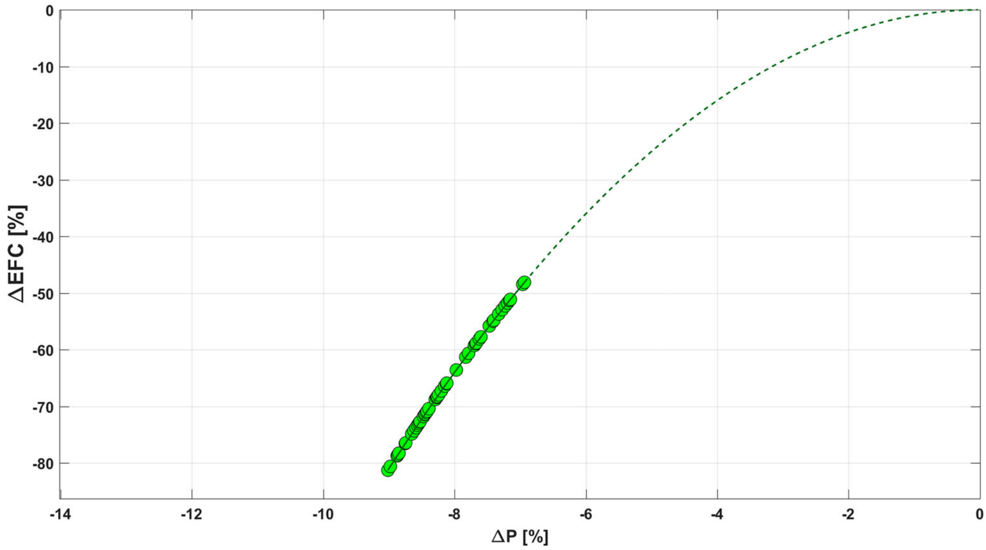

Figure 3. Error in EFC values due to the assumption of axial load for each considered section using WIM data vs. two averaged categories.

is defined by a similar equation where 'loads' values are substituted by 'fuel consumption' values.

Since the approximation caused by the use of simplified axial loads is significant, it could be useful to relate the deflection-induced EFC to the standard equivalent single axial load ESAL (18 kip = 80 kN). The EFC caused by a generic axial spectrum passing through a road section would consequently be converted into the EFC due to a given number of ESALs. In order to perform this conversion, equivalent axle load factors ($EALF_{EFC}$) are to be computed.

Figure 4 shows $EALF_{EFC}$ values of various axial load configurations and the standard single axial load whereas the equivalence has to be intended by means of the extra-fuel consumption. The equivalent factors were evaluated according to the following equation:

$$EALF_{EFC} = EFC_{(Pax)} / EFC_{(ESAL)}, \tag{5}$$

where $EFC_{(Pax)}$ is the deflection-induced extra-fuel consumption [L/km] caused by a generic axial load Pax and $EFC_{(ESAL)}$ is the deflection-induced extra-fuel consumption [L/km] caused by the equivalent single axial load.

As expected, corresponding $EALF_{EFC}$ values are higher if the axle is single rather than tandem or tridem axle configurations with similar weight due to the effect of the concentrated load. Greater deflections are expected for high and concentrated loads and the deflection-induced EFC is therefore increased. For example, a generic 160 kN axle load (2 ESALs) will generate almost 4 times the EFC if it assumed to be a single axle, 2 times for tandem, and 1.6 times for tridem, as compared to the EFC generated by an ESAL running on the same pavement. It is evident that these differences should be considered, particularly for network-scale analyses.

Temperature

Temperature affects deflection-induced EFC predictions, particularly for asphalt pavements, which are more sensitive to temperature variations because of their viscoelastic properties. Temperature varies over time and one would expect greater temperature fluctuations for higher data

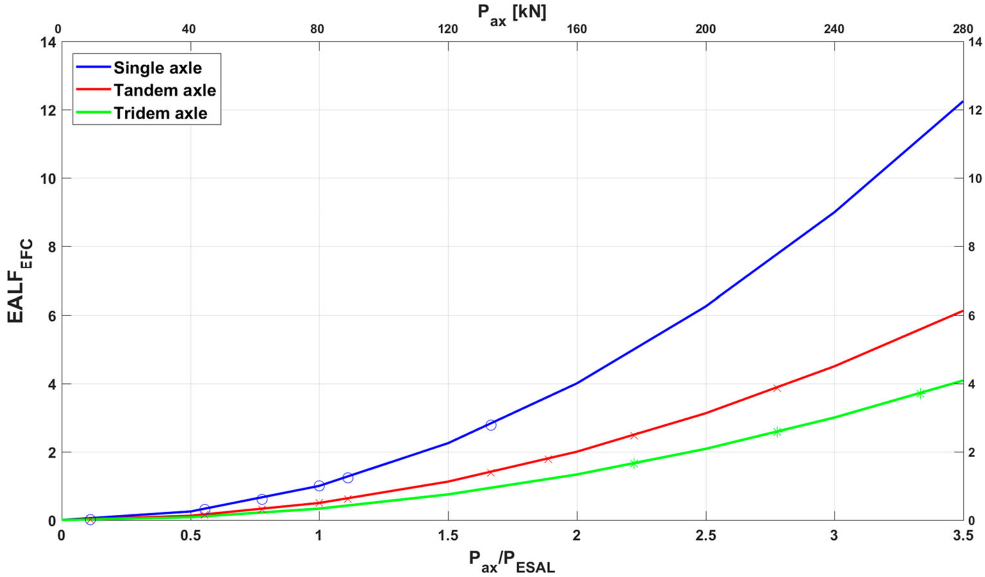

Figure 4. Conversion factors of deflection-induced EFC caused by different axial loads.

resolution (e.g. switching from monthly average values to daily average values). For this reason, a sensitivity analysis was conducted to assess the influence of temperature resolution on the estimation of deflection-induced EFC. Temperature data at different resolutions were collected from the Arizona Meteorological Network (The University of Arizona, 2016). The deflection-induced EFC was then calculated for each section using temperature data at four different aggregation levels: monthly (T_m), weekly (T_w), daily (T_d), and hourly (T_h).

$$\Delta\text{EFC [\%]} = 100\ (\text{EFC}_i)/\text{EFC}_{\text{annual}}, \tag{6}$$

where i = temperature resolution (i.e. average monthly temperature, average weekly temperature, etc.).

EFC percent increases when using temperatures at the different resolutions are shown in Figure 5 for asphalt pavements and Figure 6 for concrete pavements. In the figures, the Arizona road segments are divided according to their speed limit and each dot represents a single section (50 dots are plotted in each subplot).

Given that the EFC differences are all positive for the higher resolution temperature data, using the annual average temperatures would lead to an underestimation of deflection-induced EFC. It is also noteworthy that EFC differences for concrete pavements are lower than asphalt pavements by an order of magnitude for all temperature resolution levels, which is expected since concrete is not a viscoelastic material and its properties are not temperature dependent.

The results in Figures 5 and 6 show that the impact of using monthly, weekly, or daily temperatures is quite similar. However, the use of hourly temperature data leads to significant differences that can reach 50% higher than the other temperature resolution levels. This effect seems to be a consequence of the temperature oscillations around the annual average value. For example, using monthly temperatures means adding twelve fluctuations around the annual average temperature. The results of the temperature sensitivity analysis indicate that for the regions where the variations in temperature are significant, the use of annual average temperatures would lead to a significant underestimation of deflection-induced EFC.

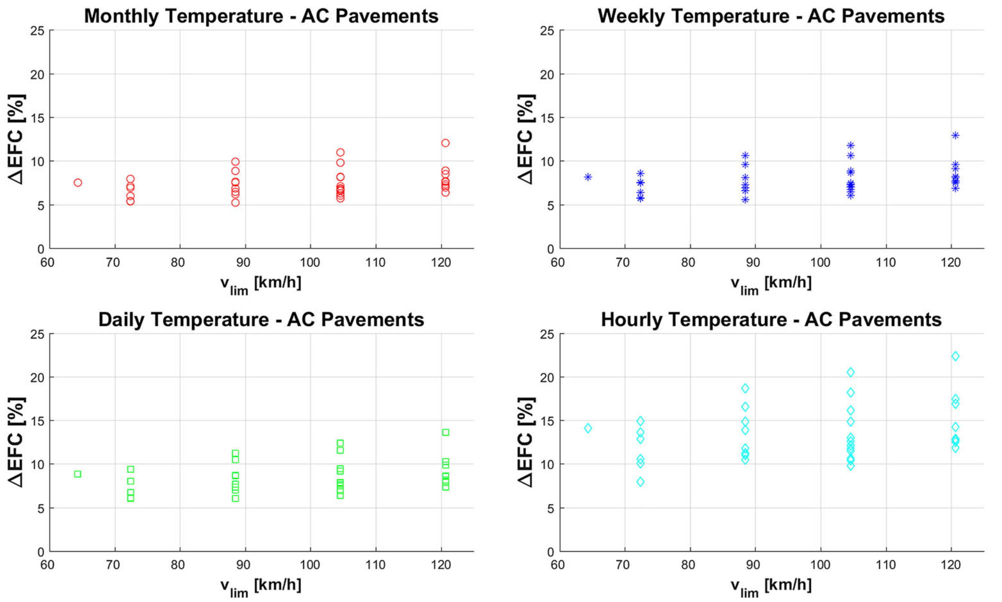

Figure 5. Percent increase in EFC of asphalt pavements due to deflection-induced PVI using hourly, daily, weekly, and monthly temperatures, compared to annual temperatures.

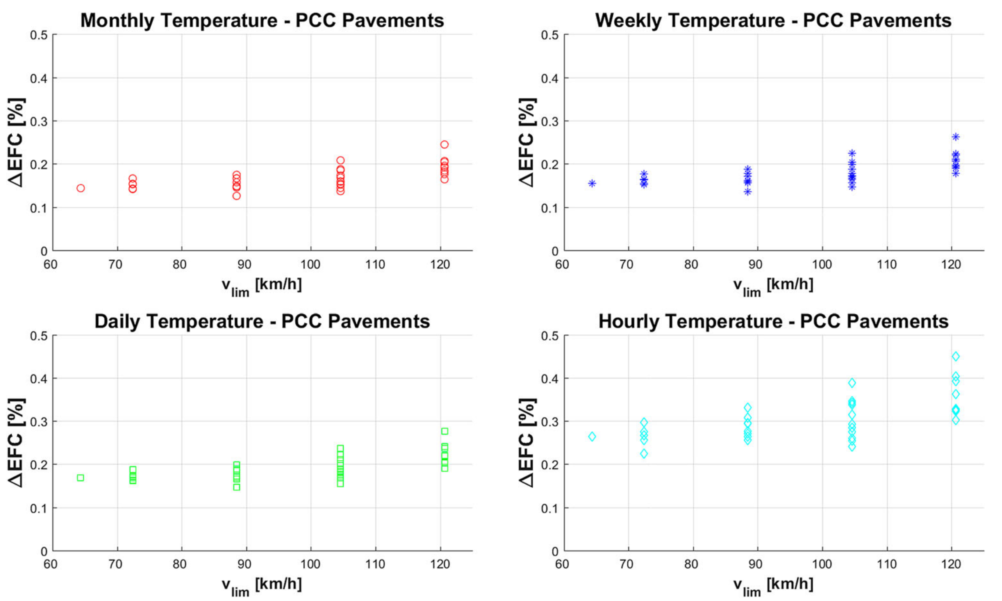

Figure 6. Percent increase in EFC of concrete pavements due to deflection-induced PVI using hourly, daily, weekly, and monthly temperatures, compared to annual temperatures.

Speed

Vehicle speed is approximated in the PVI deflection model as the speed limit of the road section under consideration. This is due to the difficulty in recording actual vehicle speed. Figure 7

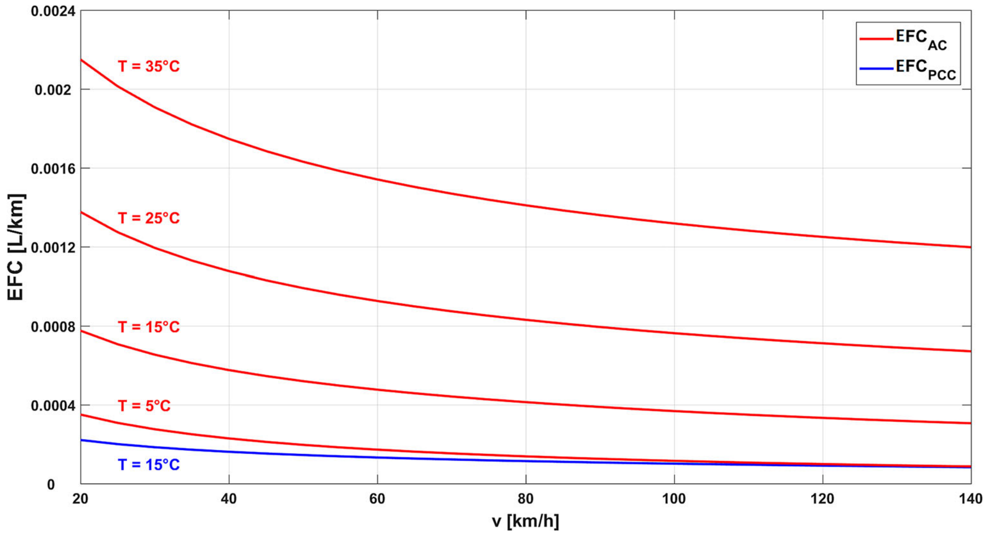

Figure 7. EFC due to deflection-induced PVI as a function of vehicle speed at a range of constant temperatures for both asphalt (AC) and concrete (PCC) pavements.

shows how the EFC varies with vehicle speed at different constant temperatures. As expected, EFC decreases with increasing speed due to viscoelastic properties of the paving materials.

Vehicle speeds rarely match the posted maximum limit and instead depend on road congestion and capacity. For example, during traffic congestion speed is a function of interactions between the vehicles in peak hours, while during free-flow conditions it is mostly affected by drivers' behaviour. Due to the difference between the speed limit and actual recorded vehicle speeds, a sensitivity analysis is necessary to evaluate the level of approximation caused by assuming the speed limit in fuel consumption calculations.

EFC was calculated with hourly recorded speed for the Arizona segments as an input parameter into the PVI deflection model to estimate the impact of the speed-limit approximation at the network level. Automatic traffic recorders were used to collect data 24 hours a day, 365 days annually, for each lane. The equipment records traffic volumes, speed, and classification of vehicles (AZ DOT, 2016).

$$\Delta\text{EFC [\%]} = 100\ (\text{EFC}_{\text{recorded speed}} - \text{EFC}_{\text{speed limit}})/\text{EFC}_{\text{speed limit}}. \tag{7}$$

Figure 8 illustrates the percentage difference in EFC when using actual recorded speeds relative to the baseline of using the speed limit for each of the Arizona segments. The x-axis refers to the difference in percentage (Δv) between the actual recorded speed and the speed limit of the road segment. A positive value indicates a recorded speed above the speed limit for that specific segment, and vice versa. The percentage is calculated as such:

$$\Delta v^y[\%] = \frac{(v^y_{average} - v^y_{limit})}{v^y_{limit}} \cdot 100, \tag{8}$$

where $v^y_{average}$ is the recorded vehicle speed for each hour of the day of the y-segment, which is then averaged over the same hours of each day of the year (i.e. annual average hourly-recorded speed); v^y_{limit} is the speed limit for the y-segment. Hourly-recorded speed was determined taking into account the speed of all vehicles passing through a specific section in one hour. Points on the

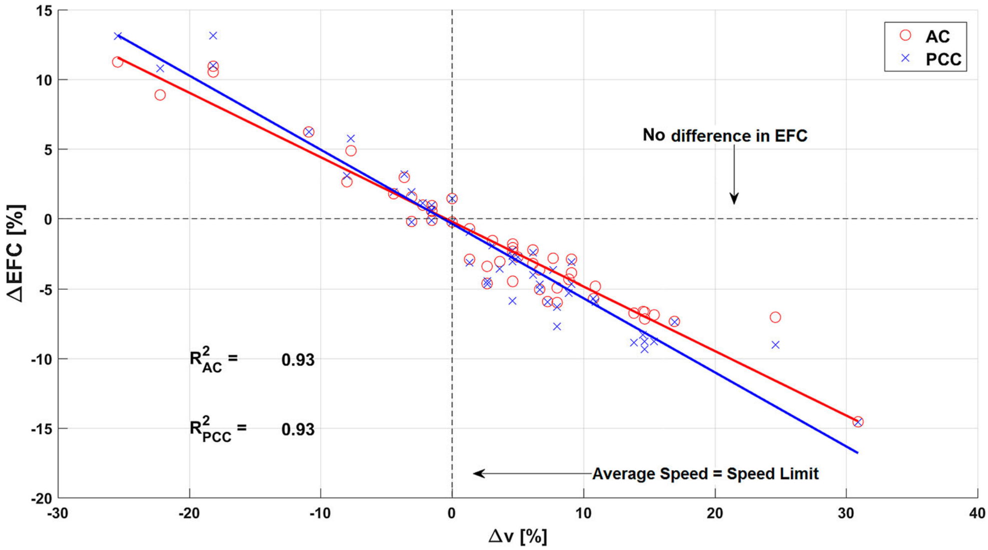

Figure 8. Percent difference in EFC due to deflection-induced PVI for annual average hourly-recorded speed compared to the baseline speed assumption of the speed limit for Arizona pavement segments. The x-axis is the percent difference in annual average hourly-recorded speed compared to the speed limit. Lines are fits for the asphalt data points (red) and concrete data points (blue), with the goodness of fit parameters shown on the plot (colour online only).

right side of the plot are for segments where the average speeds are higher than the speed limit. In these operating conditions, an EFC overestimation of up to 15% occurs if the speed-limit value is used in the PVI deflection model. By contrast, EFC is underestimated (up to almost 14%) when the road segment is congested and traffic is forced to drive below the speed limit. It should also be noted that the slope of the blue line fitting the concrete data points is slightly higher than the red line fitting the asphalt data points. This means that concrete pavements are more sensitive to speed variation than asphalt concrete pavements even if the dissipated energy is numerically lower.

It is likely that some road segments are congested during particular hours and in free-flow condition in others (e.g. weekdays vs. weekends). Averaging vehicle speeds recorded at the time of day during a weekday and a weekend day can thus lead to further differences in EFC calculations. Figure 9 shows different vehicle speed profiles of a specific road segment during weekdays (blue) and weekend days (turquoise). The two minima under the speed limit line (red) correspond to the morning and evening rush hours. The most accurate approach for road segments with this traffic pattern would be to calculate EFC during weekdays and weekend days separately.

Superposition of axial load configuration, temperature, and speed effects

There is variation throughout the day in the data used in the deflection-induced PVI model. The previous sections have highlighted the influence that such variations can have on EFC calculations. It is possible that the superposition of such effects could magnify such influence.

Figure 10 shows the trends of the hourly variation of speed, temperature, and traffic flow for an Arizona pavement segment. Two minima can be observed in the vehicle speed profile (solid blue line) due to morning and evening rush hours, while the traffic flow (solid black line) shows two peaks at about the same time of the day. In addition, the temperature profile (dotted red line) depicts a maximum in the afternoon. Deflection-induced EFC calculations would be

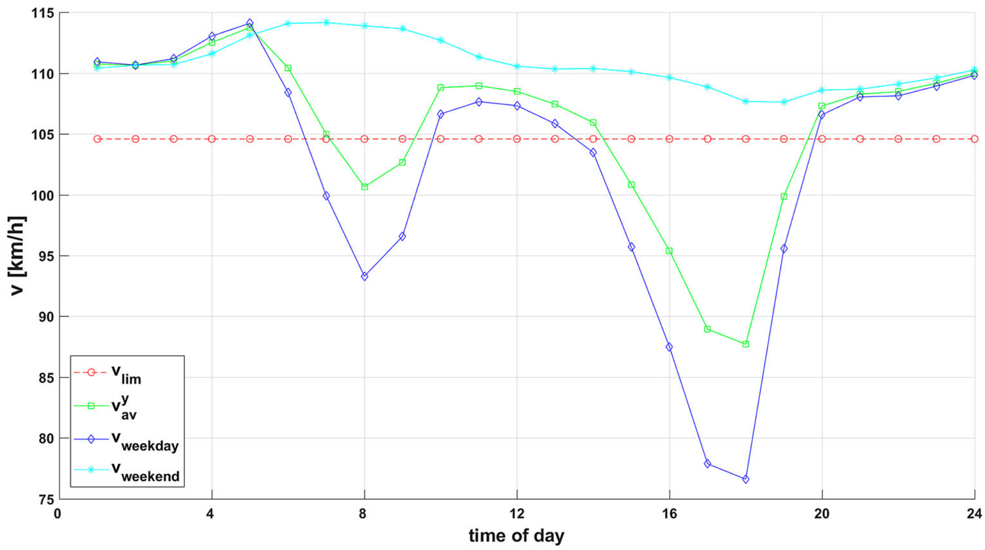

Figure 9. Average hourly-recorded speeds for an Arizona pavement segment on weekdays and weekend days, compared to the speed limit (lim) and the average (av) for the entire week (colour online only).

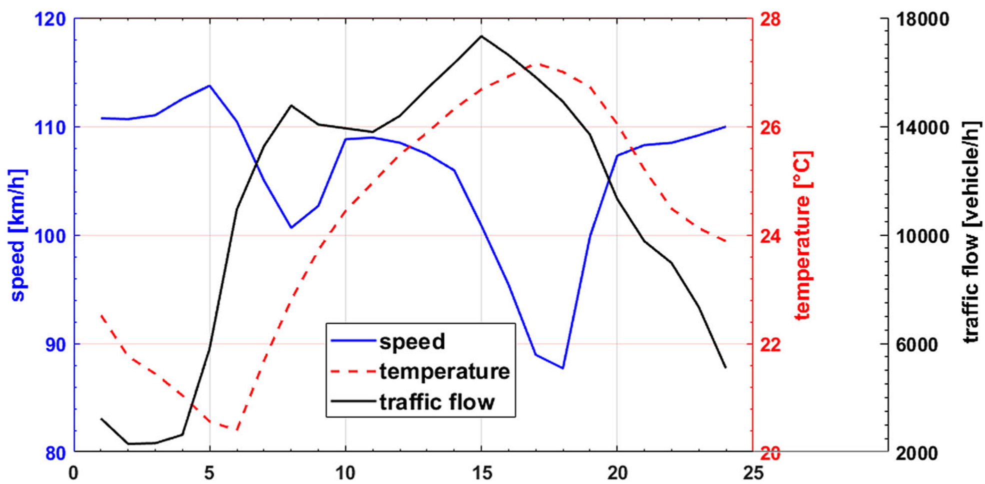

Figure 10. Hourly-recorded speed, temperature, and traffic flow on a road section (colour online only).

most affected during specific times of the day when the hourly variation of the three variables deviates most from baseline assumptions. For example, evening rush hours are characterised by high temperatures and low vehicle speeds (which both lead to higher viscoelasticity and energy dissipation in the material), and high-traffic volume (greater amount of load repetitions). The superposition of these three factors during evening rush hours would, therefore, make deflection-induced EFC values at their highest if hourly resolution of data is applied to the model.

Several scenarios of different combinations of data resolution for temperature, speed, and traffic were analysed to explore the impacts of superposition on deflection-induced EFC calculations, and are detailed in Table 3. Figures 11 (asphalt) and 12 (concrete) show the percent difference in deflection-induced EFC for the scenarios compared to EFC calculated using baseline assumptions (with constant average values) as a function of time of day because all scenarios include at

Table 3. Scenarios of input parameter resolution for a single day in a single pavement segment.

	Scenario #1	Scenario #2	Scenario #3	Scenario #4	Scenario #5	Scenario #6	Scenario #7
Temperature	*hourly*	*average*	*average*	*hourly*	*hourly*	*Average*	*hourly*
Speed	*average*	*hourly*	*average*	*hourly*	*average*	*Hourly*	*Hourly*
Traffic	*average*	*average*	*hourly*	*average*	*hourly*	*Hourly*	*hourly*

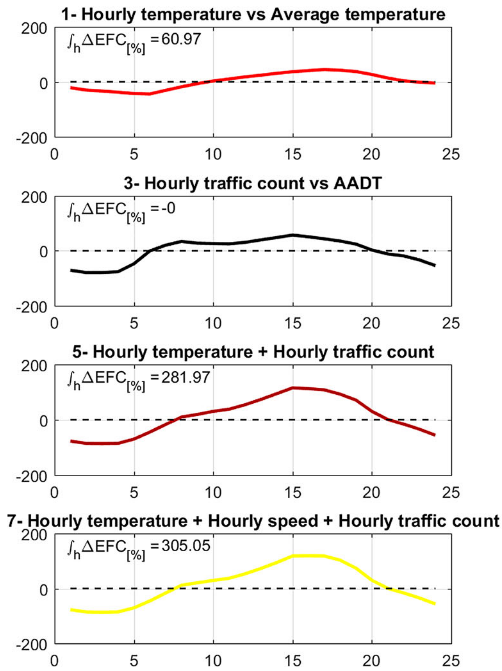

Figure 11. Percent difference in deflection-induced EFC as a function of time of day for an asphalt pavement segment compared to baseline calculations made using average and constant values for the scenarios outlined in Table 3. Each plot lists a cumulative daily EFC percent difference, $\int \Delta EFC$, which accounts for positive and negative differences.

least one set of hourly data. In addition, a cumulative daily EFC percent difference, $\int \Delta EFC$, was calculated and is presented on each plot. This cumulative daily EFC percent difference accounts for positive and negative differences.

Results for scenarios 1, 2, and 3 in Figure 11 show the impacts of changing a single parameter's resolution to hourly for an asphalt pavement segment. Increasing the resolution of temperature data to hourly has a larger impact than changing speed or traffic level. Indeed, the cumulative impact of using hourly traffic flow data is zero because energy dissipation scales linearly with the number of vehicles in the model.

The results for scenario 4 show the impact of coupling hourly temperature and hourly-recorded speed data. It is worth noting that these results are not the exact sum of the results in scenarios 1 and 2 because of the superposition effect. Speed profile positive peaks are coupled with temperature variation, which amplifies the EFC percent difference in evening rush hours while minimising the impacts from the morning rush hour. Cumulative EFC percent differences are larger for scenario 5, which includes hourly temperature and traffic count data. However, the

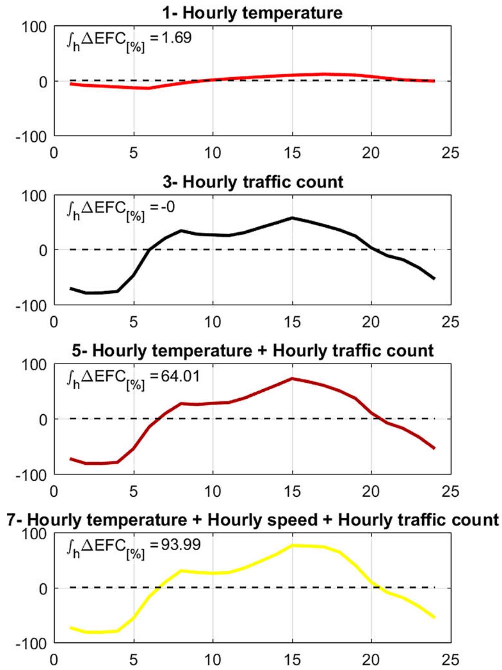

Figure 12. Percent difference in deflection-induced EFC as a function of time of day for a concrete pavement segment compared to baseline calculations made using average and constant values for the scenarios outlined in Table 3. Each plot lists a cumulative daily EFC percent difference, $\int \Delta EFC$, which accounts for positive and negative differences.

largest cumulative EFC percent difference is seen when all input parameters are included using hourly resolution. Similar trends are observed for the concrete pavement's behaviour (Figure 12), although temperature impacts are significantly less, as expected.

Deterioration sensitivity analysis results

Deflection-induced EFC in asphalt pavements due to a single ESAL including pavement deterioration (decreasing stiffness) over time was computed for different road classes defined in Table 2 (Classes A–E). There are many deterioration mechanisms such as cracking and debonding that occur during the life of a pavement and will result in the reduction in stiffness. To take into account these phenomena as a whole we model deterioration as stiffness reduction. The results in Figure 13(a) show the difference in deflection-induced EFC for a single ESAL compared to the case of constant stiffness for all of the road classes. Energy dissipation is higher for low-traffic road systems due to a reduced speed (lower speed limit) and thinner pavement layers (increased deflection); the effect is amplified over the 20 years. The increase in EFC on class E roads is significantly higher than the high-traffic class A roads. This is partially due to the fact that class A roads deteriorate slower due to the increased thickness of the pavement layers. However, incorporating the entire traffic volume for each road class (Figure 13(b)) shows that the greatest EFC occurs in class A roads. Thus, considering deterioration over the pavement life cycle combined with traffic volumes can have significant impacts on network-level EFC calculations.

Results in Figure 13 assume a do-nothing approach where no maintenance occurs on the pavements. In reality, maintenance is usually conducted on roads and will lead to enhanced

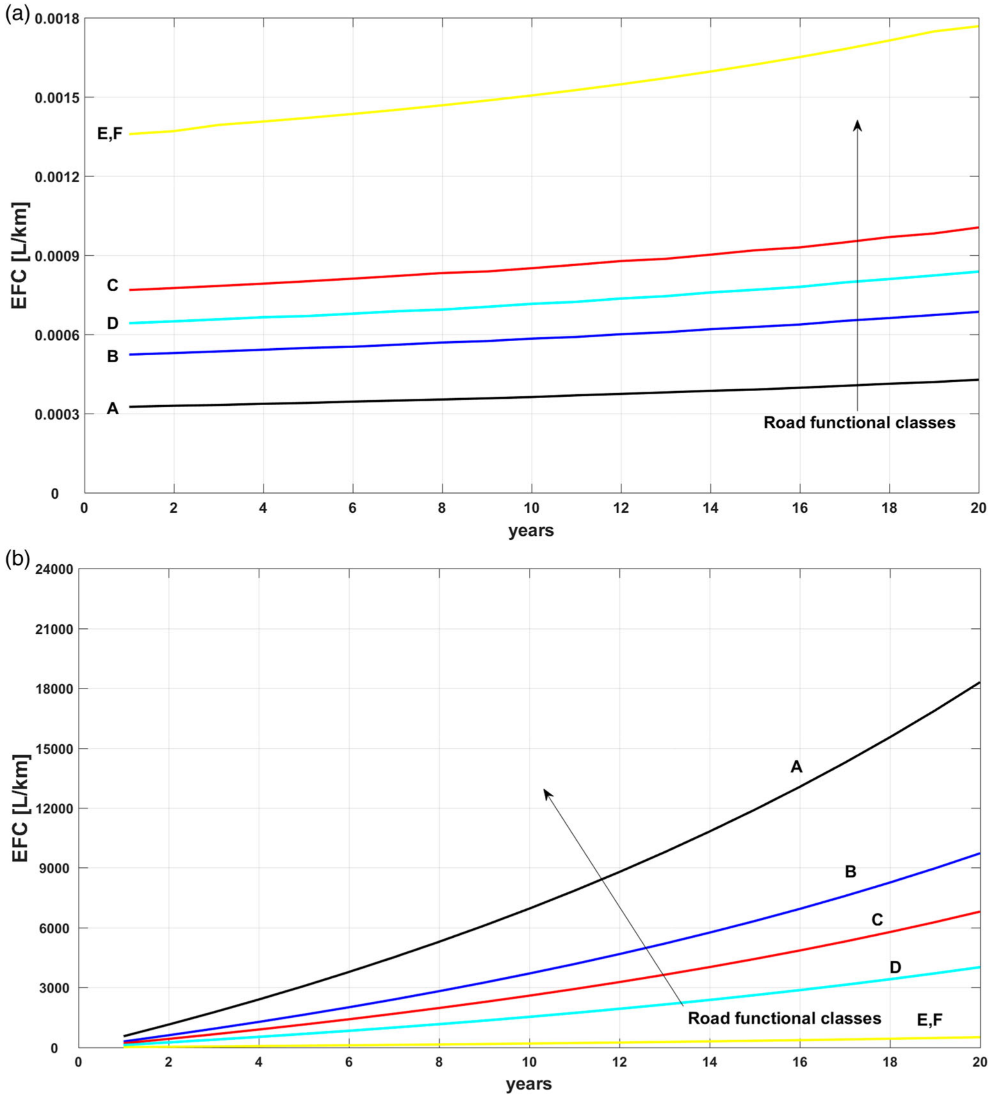

Figure 13. Difference in deflection-induced EFC over time including pavement deterioration compared to the case of constant stiffness for all of the road classes defined in Table 2 (a) for a single ESAL, and (b) including traffic volumes.

structural and functional performance. For the purpose of this analysis, a generic maintenance activity is assumed that completely restores the pavement's initial stiffness. It takes place when the pavement stiffness is equal to 75% of its initial value.

Figure 14 shows the difference in deflection-induced EFC over time including pavement deterioration compared to the case of constant stiffness when maintenance is conducted during the 20-year service life of the pavement. Dashed lines indicate results based on the do-nothing approach while solid lines show the reduction in EFC due to maintenance. The difference between the two lines represents the EFC savings due to maintenance. Such savings start after the maintenance activity, increase over time, and are higher for higher-volume roads.

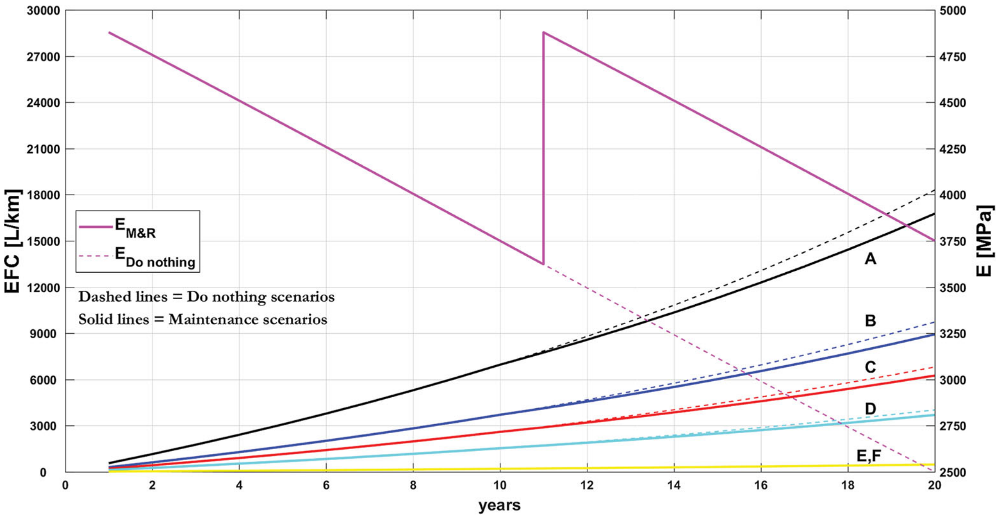

Figure 14. Difference in deflection-induced EFC over time including pavement deterioration compared to the case of constant stiffness for all of the road classes defined in Table 2 and full traffic volumes for do-nothing (solid lines) and maintenance (dashed lines) cases. Stiffness over time is plotted on the right axis.

A more detailed analysis including empirical or modelled deterioration and specific maintenance treatments is warranted. However, the present analysis demonstrates that conducting maintenance to improve the structural properties of pavements can reduce deflection-induced EFC. This is in addition to benefits from reductions in roughness-induced EFC.

Conclusions

In this paper, the sensitivity of a deflection-induced PVI model for quantifying the EFC is evaluated. The sensitivity of the fuel consumption to pavement deterioration and the resolution of axial load, temperature, and speed data was examined. The following conclusions can be drawn based on the outcomes of the analyses.

- Deflection-induced EFC scales with the square of the axial load, making this parameter one of the most significant to analyse. Indeed, the results of the sensitivity analysis showed that there are significant differences between the conventional assumption of using simplified vehicle classifications and more detailed load classifications. However, due to the difficulty in obtaining comprehensive data from weight-in-motion stations, simplifying the analysis by converting generic traffic to ESAL could be useful. EFC axial load equivalent factors were thus derived to convert the deflection-induced EFC generated by a generic load into an ESAL-induced EFC.
- The effect of temperature data resolution played a major role on EFC with its magnitude depending on the material considered in the analysis (i.e. asphalt or concrete). Varying the resolution of temperature is more significant for asphalt pavements due to the viscoelastic nature of the material. Using the highest resolution data (hourly averaged recorded values) resulted in the largest deviation from the baseline assumption of annual average temperature.
- The resolution of speed data affect EFC due to the viscoelasticity of pavement materials; energy dissipations increase when speed decreases. Real-time traffic monitoring data from

50 road sections in Arizona showed that speed is generally below the road speed limit (i.e. energy dissipation is underestimated using the speed-limit assumption) during peak hours or when approaching traffic saturation levels, while speed is above the speed limit in free-flow condition (i.e. energy dissipation is overestimated). However, at a network scale, the resolution of speed data does not have a significant impact due to the combination of congested sections and free-flow sections. For a specific pavement segment, a distinction should be made between weekdays and weekends due to the non-linearity of the traffic flows.

- The combined effect of hourly resolution data for traffic, temperature and speed on EFC was magnified during specific times of the day (e.g. evening peak hours), leading to significant differences between EFC calculations made with average data.
- The reduction of stiffness over time due to pavement distresses increases deflection-induced EFC when the pavement is analysed over its life cycle, particularly for high-volume roads. Maintenance activities that increase pavement stiffness decrease this deflection-induced EFC.

The outcomes of these sensitivity analyses can inform the use of deflection-induced PVI models for design, economic, and environmental applications. Higher resolution data for axial loads, temperature, and speed are preferred, but their relative importance will depend on the context in which they are applied and the variation of these data for that context. Climates with significant annual temperature variation, roads with significant traffic volume variations, and pavement designs that use asphalt will benefit more from the use of higher resolution data.

There are several opportunities to extend this research based on the scope and limitations of the current study. First, sensitivity analyses of other locations should be analysed, particularly colder climates and pavement networks with lower traffic levels (e.g. county or municipal networks), to determine whether the conclusions of this study using the Arizona state network hold true. Second, the sensitivity of models that quantify EFC due to other elements of rolling resistance including roughness and texture and their interactions should be evaluated in conjunction with a deflection in order to gain an overall understanding of the sensitivity of EFC calculations to these models. Third, global sensitivity analysis methods (e.g. methods based on ANOVA) can be used to quantify the excess sensitivity of fuel consumption while taking into account the uncertainties associated with the inputs. However, such analysis requires a large amount of data to evaluate the probability distribution of the inputs to the model. Forth, EFC calculations have been used in life cycle assessments (LCA) and life cycle cost analyses (LCCA) of pavements, but the outcomes of this study should be more explicitly adopted in uncertainty analyses in order to understand how the variation of EFC might affect the results of such studies. LCAs and LCCAs that adopt this robust risk assessment approach can be used to support the development of pavement design and maintenance strategies for specific contexts that fully consider life cycle environmental impacts and user costs due to EFC.

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No potential conflict of interest was reported by the author(s).

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