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ROAD ROUGHNESS AND IT'S EFFECTS ON THE INFRASTRUCTURE

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ABSTRACT

The intention of this paper is to shed light on the interaction between road roughness and the resulting road damage caused by static and dynamic wheel forces. For this purpose several trucks have been mathematically modeled as multi-body systems in great detail. The models are based on actual data of the truck industry, taking concern of geometric details as well as non-linear behavior, such as Coulomb damping in leaf springs and characteristic curves of springs and dampers.

In order to describe the relation between road roughness and its effects on road damage in a mathematical manner the first chapter of this paper deals with the description of the road in terms of the power spectral density. Assuming that the road damage depends on the fourth power of the instantaneous wheel force, and the wheel force itself is distributed Gaussian, a relationship to the road roughness can be found. Based on this mathematical approach an easy to use formula has been deduced that allows to relate road roughness data to road damage.

In order to prove, whether and under which circumstances the above mentioned formula can give a realistic estimate of road loading the previously described complex vehicle models have been used to simulate test rides over a variety of different road surfaces. The results of these runs gave the necessary information to feed the formula, especially concerning the dynamic characteristics of the single axles and axle configurations. They showed that despite of the complex and clearly non-linear behavior of the vehicles the amount of dynamic loading on the road as well as the road damage can be estimated by a rather simple formula based on the theory of linear vibrations. This formula even takes into account that there might be distinct periodic phenomena contained in the road profiles.

DESCRIPTION OF ROAD ROUGHNESS

The power spectral density (PSD) proved to be a good means to describe the longitudinal profile of a road. It allows to find a mathematical relationship between road roughness and the vibration response of vehicles moving along that road. For our purposes the displacement PSD is used, i. e. the PSD of the vertical displacement of the road profile. It is the result of a Fourier Transformation and proportional to the square of the Fourier Transform. For those who are used to the spectral presentation the PSD gives a good impression about the roughness characteristic of a road, for instance whether rather the short or the long waves are dominant in the surface. Fig. 1 shows a simplified example of a road's PSD. On the abscissa we find the 'spatial angular frequency' (2π divided by the wavelength), so we find the big wavelengths (up to 100 m) to the left and the small ones (down to 0,2 m) to the right of the graph. On the ordinate we have got the PSD. It is proportional to the square of the corresponding amplitudes. According to the graph we can conclude: the road surface includes large wavelengths with high amplitudes and small wavelengths with low amplitudes. This is typical for roads. Indeed, plotted in a log-log scale, the most roads exhibit a displacement power spectrum that can be described by a straight line having a negative slope. This line again can be described by two parameters [1]:

- the PSD corresponding to a spatial angular frequency of $\Omega_0 = 1\ m^{-1}$ (i. e. a wavelength of 6,28 m) and
- the negative slope of the line

The first parameter is called the 'spectral roughness index and shall be denoted 'RI'. It is proportional to the roughness. The higher the RI, the higher the straight line representing the PSD. RI = 1 cm^3 is typical for a good and RI = 10 cm^3 typical for a bad highway. The second parameter is called the 'waviness', w, and describes the frequency characteristic of the road. For instance, a low waviness (w = 1,5) stands for flat spectrum and so for relatively small amplitudes in the long wavelength range (left side of the graph) and relatively large amplitudes in the short wavelength range (right side of the graph). Such a road in a whole seems very flat, but exhibits noticeable short-wave deflections. It causes vehicle vibrations at higher frequencies, for instance axle hop (10 Hz). A road with a high waviness (w = 3) on the other hand has got a steeply decreasing spectrum, which shows relatively large amplitudes in the long-wavelength and relatively small amplitudes in the short-wavelength range. Such a road in a whole seems uneven, but when looked at it in detail (for instance a short part of 5 by 5 meters) it is rather even. It causes vehicle vibrations at lower frequencies, for instance body bounce (1 – 2 Hz).

Having the two spectral indices, RI and w, we can easily generate road profiles by performing the Inverse Fourier Transformation. Fig. 2 (bottom) shows the profiles of a 400-meter-segment in the left and right wheel track of a truck (track width: 2 m). In order to generate the profiles the coherence function between left and right wheel track has to be considered. Fig. 2 (top) displays the corresponding two power spectral densities. From the graph you can easily identify an RI of 1 m^{-6} = 1 cm^3 and a waviness of w = 2. Being able to generate roads with exactly defined spectral properties is helpful, when proving the relationship between road roughness and dynamic wheel loads by performing calculations in the time domain. This is being done later by using rather complex nonlinear truck models.

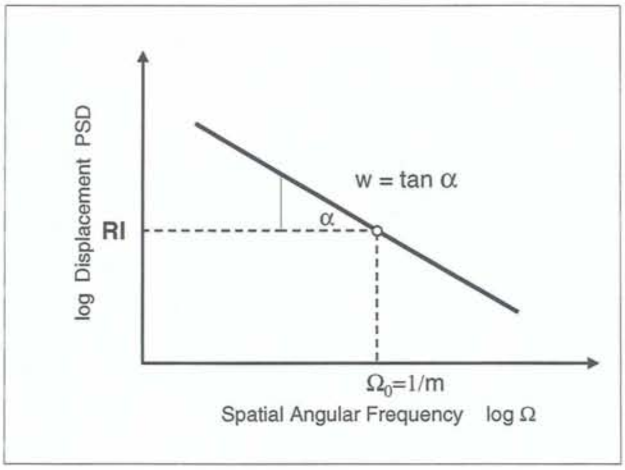


Figure 1 - Power Spektral Density of a Road: Definition of Spectral Roughness Index (RI) and Waviness (w)

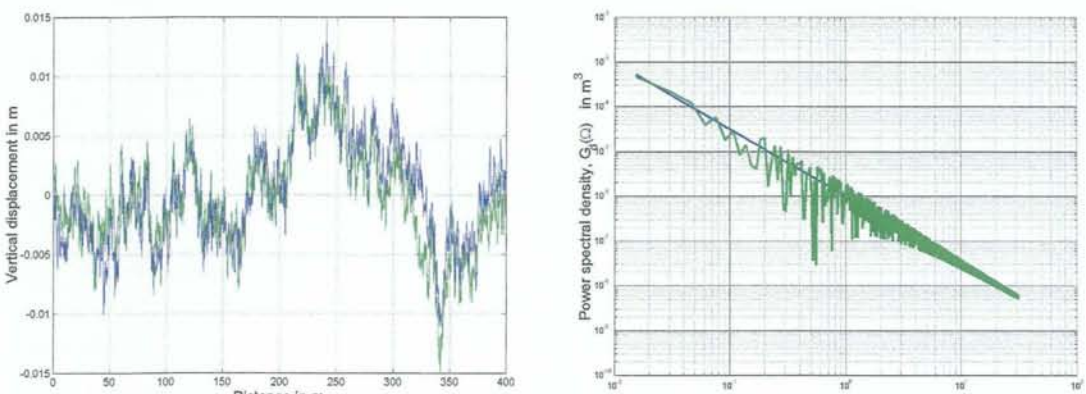


Figure 2 - LEFT: PSD for left and right wheel track (RI = 1 cm^3, w = 2).

RIGHT: Resulting longitudinal profiles for left and right wheel track.

RELATIONSHIP BETWEEN ROAD ROUGHNESS AND DYNAMIC WHEEL LOADS

It can be shown, that a mathematical relation exists between road roughness and dynamic wheel load [2]. For a linear single axle system the dynamic load factor (DLC), which is defined as the ratio of the root mean square (RMS) dynamic force to the static force,

$$DLC = \frac{RMS\,dynamictire\ force}{static\,tire\ force} \tag{1}$$

is a function of the roughness:

$$DLC^2 = v \cdot RI \cdot VDF \tag{2}$$

In the latter equation v is the speed of the vehicle (in m/s), RI is the spectral roughness index (in m^3) and VDF the Vehicle Dynamics Factor (in s/m^4). VDF represents the dynamic properties of the vehicle and is an index for the 'road friendliness' of the truck's suspension. Its rather complicated mathematical expression [3] reveals dependencies on

- the dynamic properties of the truck (such as damping, stiffness and masses),
- the speed of the truck
- the waviness of the road and
- the coherence between left and right wheel track

RELATIONSHIP BETWEEN ROAD ROUGHNESS AND ROAD DAMAGE

The repeated loading of pavements by passing trucks will eventually cause fatigue and cracking of bound materials in all types of pavements as well as permanent deformation (such as rutting) in flexible pavements. In the context of this paper road damage is looked upon as fatigue and cracking. In order to draw a relation between road roughness and road damage some kind of assumption about pavement wear has to be made. The so called "fourth power law' obtained from the 'AASHO (American Association of State Highway Officials) Road Test', conducted in Illinois between August 1956 and November 1960, is such an assumption. One of the findings of this test was that pavement wear is exponentially related to the wheel loads (the contact forces between wheel and pavement), approximately to the fourth power [4]. Even though the fourth power law is unsatisfactory as a general approach of predicting long term pavement performance and road damage, for comparison purposes, i.e. comparing different axle configurations and suspension systems in terms of their influence on road damage, it is still a plausible rule of thumb and a commonly used approach. And the latter is the objective of this paper: to propose an indicator for 'road friendliness', which considers the dynamic properties of the truck suspension, and to rate different types of trucks.

Provided, that the dynamic wheel loads are distributed normally, which has been proved by experiments [5], it can be shown that the mean value of the fourth power of the wheel load can be calculated from the static wheel load, F_{stat}, by the following equation [6]:

$$\overline{F^4} = F_{stat}^4 (1 + 6DLC^2 + 3DLC^4) \tag{3}$$

Taking into account that the DLC in most cases is beyond 0,3 (which denotes the instant when the wheel is beginning to loose contact to the ground) the fourth power term in the above equation can be neglected. By substituting Eq.(2) for DLC^2 Eq.(3) reduces to the following,

$$\overline{F^4} = F_{stat}^4 (1 + 6 \cdot v \cdot RI \cdot VDF) \tag{4}$$

In order to account for the influence of the wheel configuration (single or dual tires) and tire contact pressures the following expression for a so called 'road stress factor' was proposed [6]

$$road\ stress\ factor = \overline{(\eta_I \eta_{II} F)^4} \tag{5}$$

with η_I tire configuration: 1 for single and 0,9 for dual tires

η_{II} contact pressure: 1,1 / 1,0 / 0,9 for 0,9 / 0,7 / 0,5 N/mm^2

Substituting Eq.(4) into Eq.(5) we get:

$$road\ stress\ factor = (\eta_I \eta_{II} F_{stat})^4 (1 + 6 \cdot v \cdot RI \cdot VDF) \tag{6}$$

Because the road stress factor yields rather large values (proportional to F_{stat}^4), it is referred to a 10-ton axle for the further considerations. The result is the amount of pavement distress expressed in number of (quasi-static) passes of a 10-ton reference axle. This quantity is an extended but essentially similar formulation of the 'load equivalent factor' (LEF) derived from the ASHOO road test. It will be denoted 'load equivalent factor' LEF* in this context. Thus Eq.(6) becomes:

$$LEF^* = (\eta_I \eta_{II} F_{stat} / 10t)^4 (1 + 6 \cdot v \cdot RI \cdot VDF) \tag{7}$$

As can be seen the LEF* consists of a quasi-static and a dynamic part. The dynamic part is the part of pavement distress, that is caused by roughness, while the quasi-static part denotes that part, that theoretically would occur in the absence of any roughness. This is a mathematical formulation of the fact, that with increasing roughness the loading and thus the damaging increases. The following equations can be set up:

$$LEF^* = LEF^*_{stat} + LEF^*_{dyn} \tag{8}$$

$$LEF^*_{stat} = (\eta_I \eta_{II} F_{stat} / 10t)^4 \tag{9}$$

$$\frac{LEF^*_{dyn}}{LEF^*_{stat}} = 6 \cdot v \cdot RI \cdot VDF \tag{10}$$

It is noteworthy that Eq.(10) denotes the increase in pavement distress caused by the roughness. According to this equation the increase is a function of speed, roughness and vehicle dynamics. So we have got a rather simple means for comparing different trucks and suspension systems concerning their influence on road damage.

PROVING THE MATHEMATICAL APPROACH

The mathematical approach presented in Eq.(7) is based on a number of assumptions, specifically the assumption of linear system behavior of the trucks. In order to prove whether real trucks behave that way, four trucks, typical for European highways, have been modeled in detail. The three-dimensional multi-body systems consider the nonlinear behavior of steel (coulomb friction) and air springs as well as of the hydraulic dampers. The geometric and dynamic data are taken from state-of-the-art truck development. The four trucks are:

- a 2-axle truck, 18 ton gross weight, steel sprung
- a 3-axle truck, 25 ton gross weight, air sprung
- a 5-axle truck trailer, 40 ton gross weight, air sprung
- a 5-axle tractor-trailer, 40 ton gross weight, front axle steel sprung, rest air sprung

The four vehicles are shown in Figs. 3 to 6.

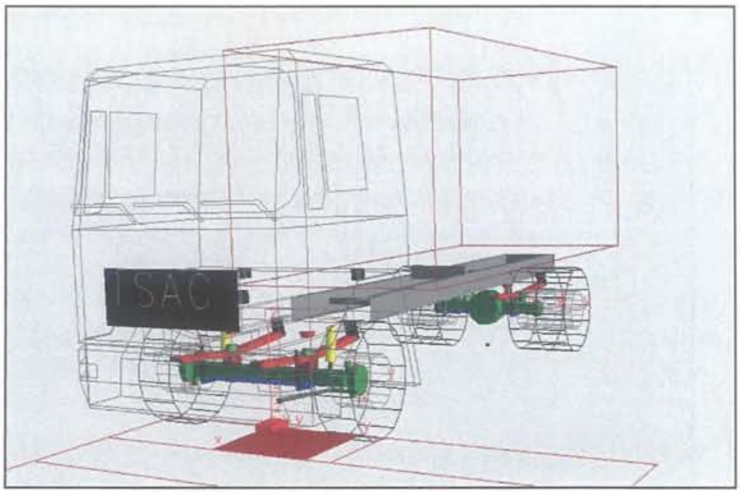


Figure 3 - 2-axle truck, 18 ton gross weight, steel sprung.

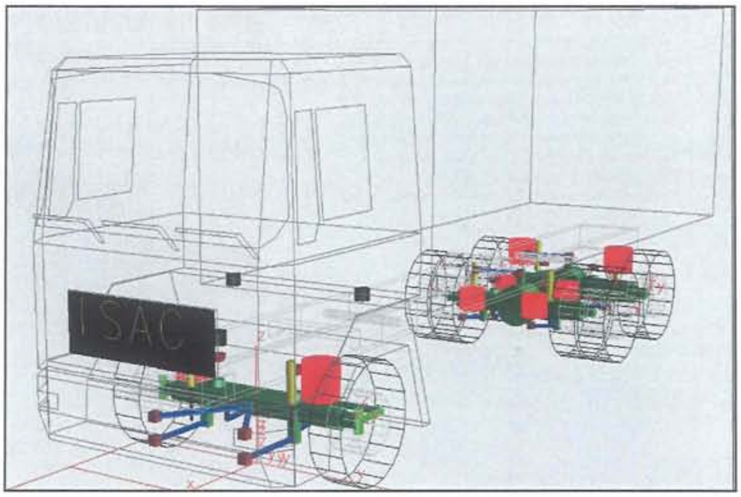


Figure 4 - 3-axle truck, 25 ton gross weight, air sprung

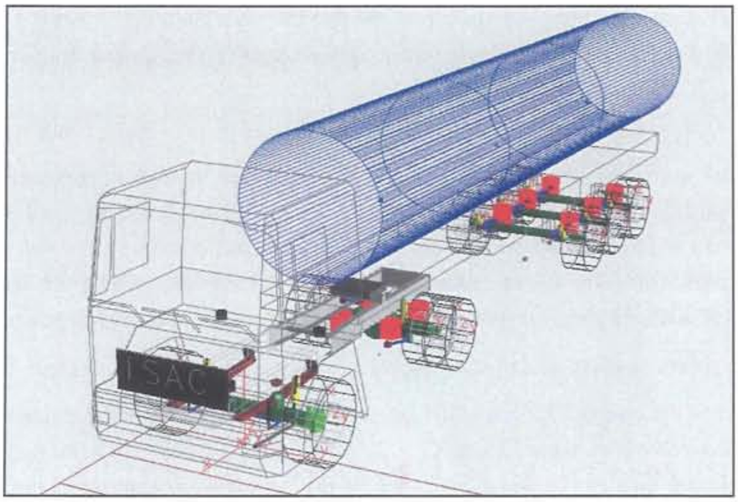


Figure 5 - 5-axle tractor-trailer, 40 ton gross weight, front axle steel sprung, rest air sprung

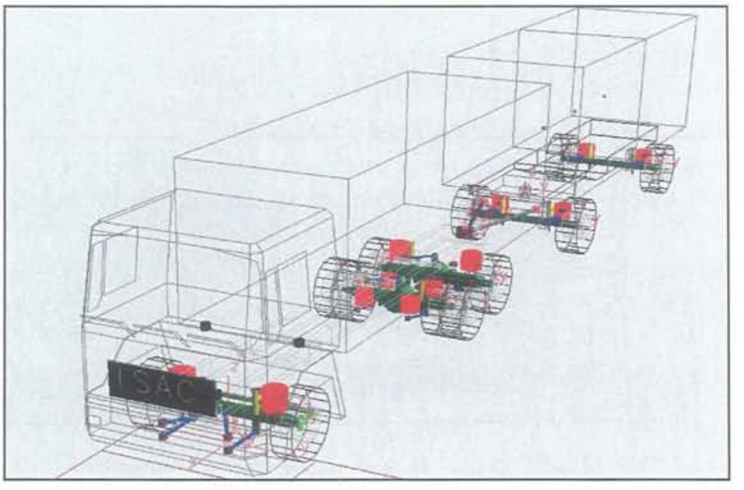


Figure 6 - 5-axle truck trailer, 40 ton gross weight, air sprung

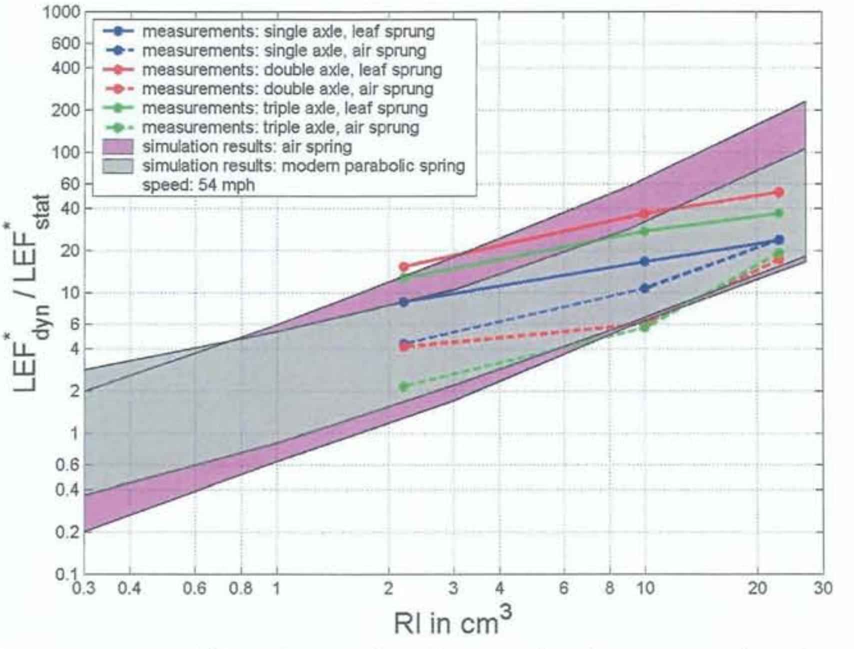


Figure 7 - Amount of pavement distress due to road roughness as referred to a very smooth road; comparison with results from (5).

Simulated test rides over a variety of different roads were performed in order to prove whether Eqs.(7) and (10) apply for non-linear dynamic systems as well. For that reason 20 different roads (RI [cm^3] = 0,3 / 1 / 3 / 9 / 27 and w = 1,5 / 2 / 2,5 / 3) were generated, which had to be driven by each of the vehicles with a speed of 24 m/s, i. e. 53,7 mph. The wheel loads were measured and, summed up to axle loads, raised to the fourth power and finally averaged. In comparison with the corresponding static axle loads, raised to the fourth power and averaged as well, the additional pavement distress due to the roughness of the road (which is denoted $LEF^*_{dyn} / LEF^*_{stat}$ in equation 10) could be determined for each of the axles. The results are shown in Fig. 7 summarized for leaf and air sprung axles respectively. They spread from 0,2 to 2 % for very even roads up to 20 to 200 % for very uneven roads, dependent on the type of axle and the waviness of the road. It is astounding that the leaf springs performed as well as the air springs, except in the case of very good roads, where the leaf springs tended to cause higher pavement distress. This is due to the Coulomb friction, which becomes apparent in some kind of 'stick-slip mechanisms' only on very smooth road surfaces. The leaf sprung axles were fitted with modern low-friction parabolic springs. The result confirms the observation that modern well-maintained leaf sprung suspensions, operated under optimum loading conditions, can compete with air sprung suspensions. The rather "bad" come-off of the air sprung suspensions on the other hand was mainly caused by the front suspension of the 25-ton truck. In order to achieve good driving comfort the manufacturer decided to equip this type of truck with a rather low damped front axle, which in turn causes higher dynamic wheel loads and, as a result, higher pavement wear.

The question that was supposed to be answered by this chapter was: can the additional part of pavement distress that is due to the roughness of the road be expressed in terms of a linear function of the roughness as shown in Eq.(10)? Fig. 7 confirms this assumption: dividing the curves by the abscissa (i.e. the road roughness RI) yields in almost horizontal curves (not shown), which is a strong indicator for the linear dependency. Dividing them by ($6 \cdot v \cdot RI$), see Eq.(10), yields in vehicle dynamics factors (VDF) between 45 and 450 s/m^4 , which very well agree with $VDFs$ mentioned in the literature ranging from 60 to 400 s/m^4 [7]. Additionally, Fig. 7 contains the comparison with results found in the literature. The University of Hannover conducted a series of measurements [5], that confirms the theoretical results found here.

RESULTS FOR THE WHOLE VEHICLE

As 'load equivalent factors', LEF^* , can be determined for single axles, they can be determined for a whole vehicle. Corresponding to Eq.(10) a 'vehicle dynamics factor', VDF , for the whole vehicle can be defined. So Eqs.(8) to (10) apply to the whole vehicle as well, except for a little modification in Eq.(9) to consider the n axles of the truck:

$$LEF^*_{stat} = \sum_{i=1}^{n} (\eta_I \eta_{II} F_{stat,i} / 10t)^4 \tag{11}$$

Fig. 8 shows the results for each the four vehicles. The LEF^* consists of a 'static part', LEF^*_{stat} , caused by the static weight, and a 'dynamic part', LEF^*_{dyn} , caused by the road roughness (see Eq.8). The static part (Eq.9) is the value at the very left of the graph. The dynamic part (Eq.10) is a function of the roughness. Its slope is dependent on the static LEF*, the speed and the 'vehicle dynamics factor', VDF.

As can be seen, the static LEF* for the 18-ton truck is about 1, for the 25-ton truck it is about 1,5 and for the 40-ton vehicles it is about 2. This means that on a very smooth road a 25-ton truck (fully loaded) damages a road about 50% and a 40-ton truck about 100% more as compared to a 18-ton truck. This is astounding at first, when thinking of the assumption that the weight influences the road damage by the fourth power. But considering the tire configurations of the different axles (see factor η_I in Eq.9) the above mentioned results are yielded. With increasing road roughness the LEF* increases as well, up to 100% in the case of the tractor-trailer on a poor road (RI = 27 cm^3).

The shaded areas mark the results of the simulated test rides of the four trucks, covering a waviness of w = 1,5 to 3. They were calculated basically by using Eq.(5), i.e. multiplying the axle loads by the factor ($\eta_I / 10t$) (the factor η_{II} was set to 1), raising them to the fourth power, averaging them over the road's length and summing up over all the axles of the truck. This was done for each of the trucks and each of the 20 different roads that were driven.

The four bold straight lines in Fig. 8 are the result of a fitting according to Eq.(7) with vehicle dynamics factors VDF of 70 s/m^4 (for the tractor-trailer) to 100 s/m^4 for the 18-ton-truck. From figure 5.1 it is obvious that up to a roughness of RI = 10 cm^3 (which corresponds to a bad highway) the damaging influence of the four trucks can well be described by this equation assuming an average VDF for a waviness between w = 1,5 and 3. Because of it's importance the equation is repeated here:

$$LEF^* = LEF^*_{stat}(1 + 6 \cdot v \cdot RI \cdot VDF) \tag{12}$$

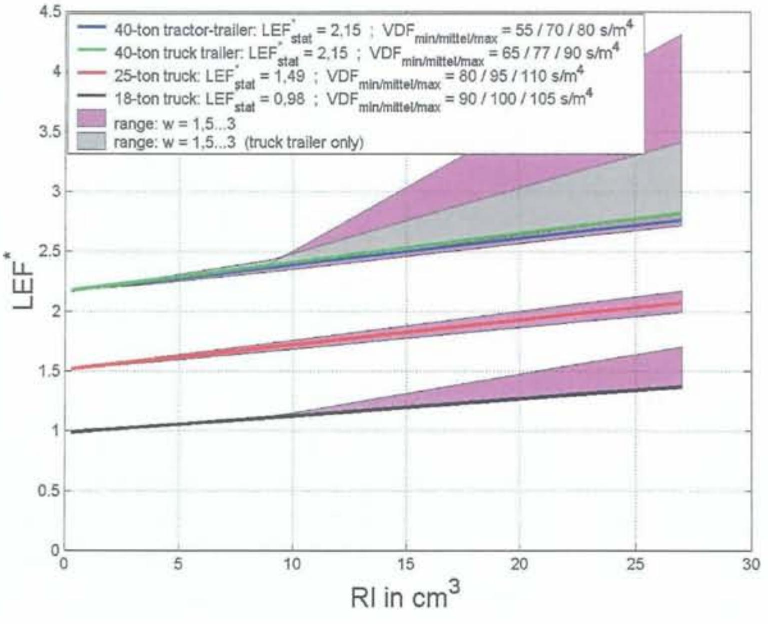


Figure 8 - Pavement Distress caused by different vehicles at a speed of 54 mph

For a larger roughness the spreading caused by the different waviness is too large in order to describe the behavior of the truck by an average VDF. Still, for a waviness of 2 (which is about the average waviness for highways) it was found that the equation very well fits the results of the simulated test drives over the whole range of roughness from 0,3 to 27 cm^3.

Summarizing the findings, table 1 contains the LEF^* and the VDF, for both: a roughness up to 10 cm^3 (applicable to all kinds of roads) and a roughness up to 27 cm^3 and more (applicable only to roads with a waviness of about 2).

Table 1 - Static Load Equivalent Factor and Vehicle Dynamics Factor

	LEF^*_{stat} fully loaded	VDF in s/m^4 for RI < 10 ^{3}cm	VDF in s/m^4 for w = 2
18-ton-truck	1	100	97,5
25-ton-truck	1,5	95	83
40-ton-truck-trailer	2,15	77	77
40-ton-semi-trailer	2,15	70	66

CONSIDERING PERIODIC PHENOMENA IN THE ROAD SURFACE

The examinations have been extended to road surfaces with combined irregular and periodic phenomena in that way, that some of the road profiles used before have been superimposed by periodic longitudinal profiles of different amplitude. The periodic profiles were

- sinusoidal profiles with amplitudes of 2,5 / 5 / 10 mm exciting the trucks in the range of 1...2 Hz and 10 Hz, which is about the frequency of the sprung mass and the axle respectively
- "tooth-saw"- profiles with average step heights of 2,5 to 20 mm corresponding to average "amplitudes" of 1,25 /2,5 / 5 / 10 mm, representing concrete plates of 5 meter length

For this investigation five "basic" roads with a roughness index RI = 0,3 / 1 / 3 / 9 / 27 cm^3 and a waviness w = 2 have been used. The driven speed was 53,7 mph as before.

The results of the simulated test rides are exemplary shown in Fig. 9 in case of the 40-ton tractor-trailer on the "saw-tooth" profile. It is noticeable, that the increase in LEF^* is independent of the roughness. This was found for all of the four trucks and all of the above mentioned excitations except for one: the excitation with 10 Hz in combination with the maximum amplitude of 10 mm. In this instance the LEF^* was highest for very low RI (i. e. almost pure sinusoidal excitation) and decreases with increasing roughness (i. e. increasing disturbances in the harmonic signal), which is understandable. In all the other instances the results can be mathematically expressed by basically adding a "P-value" to Eq.(12) representing the periodic part of the excitation:

$$LEF^* = LEF^*_{stat}(1 + P + 6 \cdot v \cdot RI \cdot VDF) \qquad (13)$$

For the example in Fig. 9 the P-value is 0,06 and 0,2 for a step height of 10 and 20 mm respectively, otherwise zero (see legend). This means that pavement wear, measured in LEF^*, increases by 6 and 20 % respectively. The differences between simulated test ride results and the approximation through Eq.(13) are below 3% for a roughness index below 10 cm^3 and below 10 % for an RI up to 27 cm^3. Fig. 10 summarizes the results. The completely air sprung vehicles (the 25-ton truck and the 40-ton truck trailer) turned out to be most sensitive to periodic excitations through concrete plates (about 5 Hz at 54 mph) and harmonic excitation with 10 Hz (resonance of the axle), while least sensitive to harmonic excitation with 1 to 2 Hz (resonance of the sprung mass). Excitations typical for concrete roads as well as harmonic excitations with 1 to 2 Hz caused a maximum increase in pavement damage of about 30 to 40%, while excitations with 10 Hz caused an increase of 50 to 250 %.

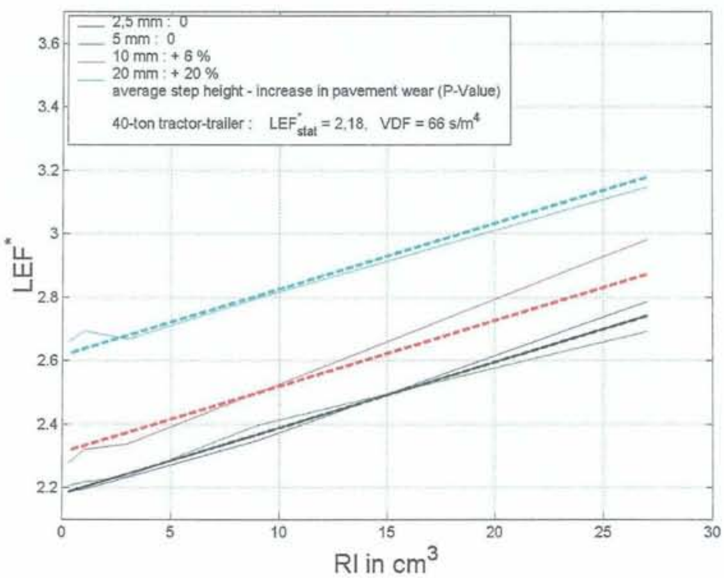
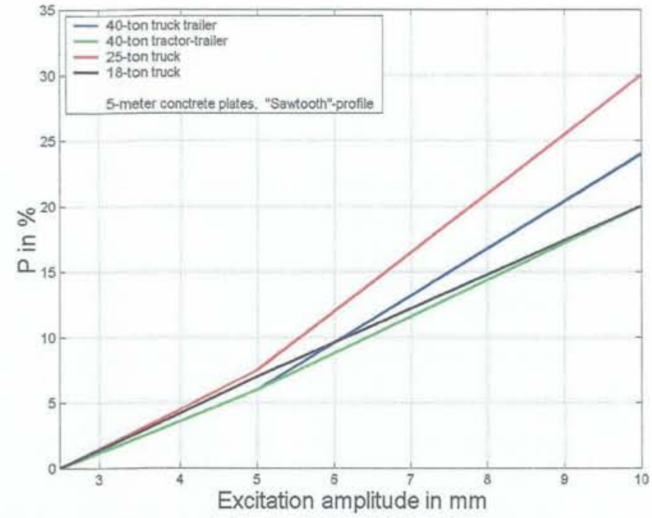
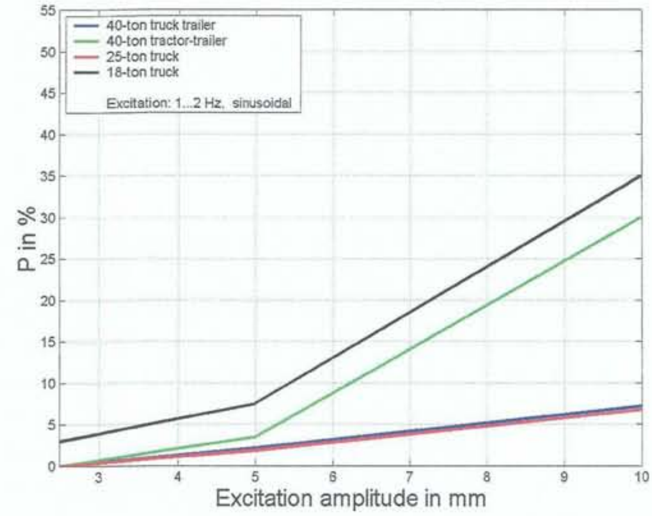


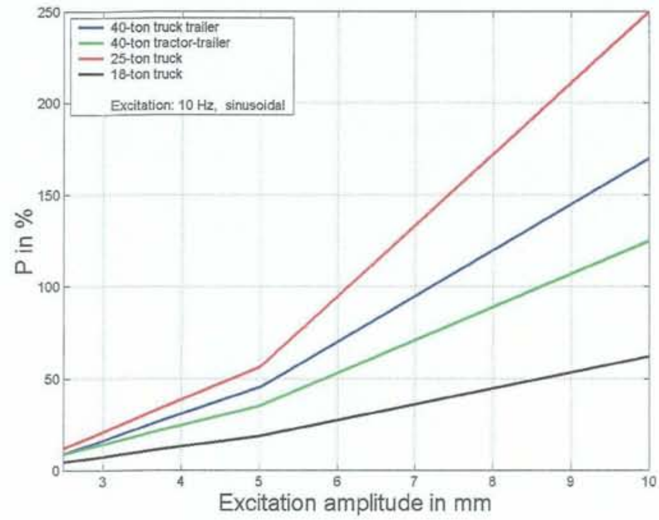
Figure 9 - The influence of „tooth-saw" profiles on the road damage, 40-ton tractor-trailer



a)
'saw-tooth'-profile
concrete plates (5m)



b)
sinusoidal excitation
1...2 Hz



c)
sinusoidal excitation
10 Hz

Figure 10 - Increase in pavement wear by periodic excitation (P-value)

CONCLUSION

The intention of this paper is to shed light on the interaction between road roughness and road damage caused by static and dynamic wheel forces. For this purpose the first chapter deals with the description of the road in terms of the power spectral density (PSD). Furthermore it can be shown that a mathematical relationship exists between PSD and dynamic wheel loads. In a third step the static and dynamic wheel forces are being linked to road damage by using the "fourth power law", obtained from the results of the ASHOO Road Test. The result is an equation that allows to relate road roughness data to road damage. This equation has been extended to periodic phenomena later and proved by rather detailed non-linear multi-body systems representing four different trucks. For it's importance to this paper it shall be repeated here:

$$LEF^* = LEF^*_{stat}(1 + P + 6 \cdot v \cdot RI \cdot VDF) \qquad (14)$$

The equation says that pavement distress with respect to fatigue and cracking (measured here in terms of a 'Load Equivalent Factor', LEF^*) can be understood as a process caused by a quasi-static (LEF^*_{stat}) and a dynamic contribution of the truck, the latter resulting from the roughness (indicated by the 'Roughness Index', RI) and periodic phenomena eventually contained in the road surface (expressed by 'P'). The dynamic part resulting from periodic phenomena turned out to be independent of the roughness except for excitations with very high amplitudes at resonance frequency of the axles. The dynamic part resulting from the roughness is, besides the RI, dependent on the vehicle speed, v, and the 'Vehicle Dynamics Factor', VDF, which describes the dynamic properties of the truck, actually the 'road friendliness' of the suspension system. The 40-ton tractor-trailer was found to have the most and the 18-ton truck the least 'road-friendly' suspension, 70 and 100 s/m^4 respectively.

The VDF proves to be a suitable means being able to describe the dynamic properties of the truck in a distinctive way. It applies for an RI up to 10 cm^3 and the maximum permitted speed. For roads up to RI = 10 cm^3 (which corresponds to a bad highway) and maximum permitted speed roughness accounts for up to ($6 \cdot 24 \, m/s \cdot 10 \cdot 10^{-6} m^3 \cdot 100 \, s/m^4$) = 15 % of the pavement distress caused by the truck. For a higher roughness (here: 27 cm^3) Eq.(14) only applies, if the waviness is about 2. Here a 40% increase is found. These results comply very well with results found in the literature [8]. For a waviness other than 2 roughness is partially found to have a much higher influence: in case of the tractor-trailer it can increase the pavement wear up to 100% (see Fig. 8).

These are by definition (see Eq.3) values that are averaged over the length of a road. Peak values are 25 % to 200% higher depending on the roughness [3].

If periodic phenomena are contained in the road surface, the pavement distress is even enhanced. Excitations in the range of the axle resonance turned out to have the highest influence on pavement wear. An amplitude of 5 mm can lead to a 50%-increase (P = 0,5) in pavement wear (mean value) and an amplitude of 10 mm in combination with a low RI (1 cm^3) even enlarges the pavement distress by up to 250% (P = 2,5; see Fig.10). Excitations in the range of 1 to 2 Hz (resonance of the sprung mass) and "saw-tooth"-profiles encountered on concrete roads turned out to have only a tenth of that effect (P = 0,06 and 0,25 for an amplitude of 5 and 10 mm respectively).

The findings presented in this paper allow to qualify vehicles with respect to their 'road friendliness' and their contribution to pavement wear in terms of fatigue and cracking. The formula developed doesn't claim to yield *quantitative* results regarding pavement damage (which depends on a wider range of parameters than considered here), but rather allows to compare and rate different vehicles and is supposed to give a better understanding of the influence of road roughness on pavement wear. In this way the contribution of this paper should be understood.

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