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A Review of 'Road-Friendly' Suspensions

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Abstract

The high cost of maintenance of highways and road networks, because of premature road failure due to heavy traffic have caused global concern. Fluctuating component of tire-road force is the main contributor to road damage along with other environmental factors. This can be reduced by selection of optimal values of suspension parameters. Hence, main objective of this paper is to provide a review of available literature on "road friendly" suspension design. We explore road damage mechanisms, criteria used to characterize the road damage and influence of suspension parameters on road damage. Conclusions of different studies are presented along with scope for further research.

Keywords: Road damage, Fourth power law, Suspension.

1 Introduction

The ride comfort and road holding with limited rattle-space are the conventional performance criteria for any vehicle suspension design. But nowadays, in case of heavy goods vehicles (HGVs), awareness is increasing that the suspension system must satisfy an additional criterion, namely road friendliness, i.e. it should minimize the damage caused by the heavy goods vehicle to the road. The forces of interaction between the tires and the road induce stresses in the pavement, which ultimately lead to road failure. For passenger vehicles the contact forces between tires and road are too small to cause significant pavement damage. For these vehicles ride comfort is the major criterion for suspension parameter selection. However, for HGVs the contact forces between tires and road are considerable and hence for these vehicles, suspension parameters must be selected so as to minimize road damage. Over the past few years, there has been growing concern over maintenance of highways throughout the world. Some important legislations that have come into practice recently are: (i) In 1992, Council for European communities issued restrictions on the use of wide single tires that caused increased road damage [1], (ii) In India, Motor Vehicle Act (2000) has hinted possibilities of introduction of vehicles with 'road friendly' suspensions [2], (iii) Directive 2002/15/EC of the European Parliament and the council also stresses the importance of roadway maintenance and promotes ways to favor the same [3].

India has 3.34 million kilometers of road network, which is the second largest in the world and 65% goods transport is done through road sector. Also, prestigious projects like Golden Quadrilateral (cost Rs 54,000 crores) are being undertaken [4]. The construction cost per kilometer per lane is approximately Rs 1 crore. According to Planning Commission presentation, India loses Rs. 10,000 crores per year due to 'Inadequate capacity and poor quality of roads' [5]. It is speculated that the majority of damage was traffic induced, with heavy vehicles being the major contributors. Owing to such high costs of road construction and their subsequent maintenance it becomes necessary to look into the road damage issue more closely. The main objective of this paper is to give an up-to-date review of the literature concerned with road damage caused by HGVs and the ways to modify the suspension system in order to reduce road damage. To do this, one has to study the literature related to following:

i) Studying road damage in detail, its causes and types,
ii) Defining the criteria that can be used to characterize road damage caused by heavy vehicles,
iii) Studying the influence of vehicle parameters on road damage leading to optimal selection of these parameters.

2 Roads

2.1 Types of roads

Road surfaces (or pavements) are classified as *flexible*, *composite* or *rigid*, based on their method of construction [6, 7]. A *flexible* pavement consists of one or more layers of asphalt supported by a granular sub-base. *Composite* pavements consist of a flexible surface layer supported by a stiff Portland Cement Concrete (PCC) base; and *rigid* pavement consists of a layer of PCC on a granular foundation.

2.2 Modeling road roughness

Road surfaces can normally be considered as random with a Gaussian probability distribution, provided that the occasional large irregularities such as potholes are treated separately [6]. It is generally found that the amplitude/ wavelength characteristics of roads can be characterized in terms of spectral density of the profile height. Most commonly used methods for modeling road profile variations are as follows:

i) *The Draft ISO Formulation* [8]:

The spectral density $S_u(\kappa)$ of road height u is classified as follows:

$$S_u(\kappa)=\begin{cases} S_u(\kappa_0)\left(\dfrac{\kappa}{\kappa_0}\right)^{-n_1} & \dfrac{\kappa}{\kappa_0}\le 1 \\ S_u(\kappa_0)\left(\dfrac{\kappa}{\kappa_0}\right)^{-n_2} & \dfrac{\kappa}{\kappa_0}>1 \end{cases} \quad (1)$$

where, κ = wavenumber, cycles/m
κ_0 = datum wavenumber, cycles/m
$S_u(\kappa)$ = displacement spectral density, m^3/cycle
$S_u(\kappa_0)$ = spectral density at κ_0, m^3/cycle

The values of constants recommended in [8] (corrected later in [9]) are $n_1=3$, $n_2=2.25$, $\kappa_0 = 1/(2\pi)$ cycles/m and $S_u(\kappa_0)$, in the corrected ISO standard for road roughness is given as: $S_u(\kappa_0)/10^{-6}$ m^3/cycle = 2-8 for very good road class, 8-32 for good road class, 32-128 for average road class, and 512-2048 for very poor road class. Figure 1 shows the draft ISO classification along with the spectral density of TRL test track in UK.

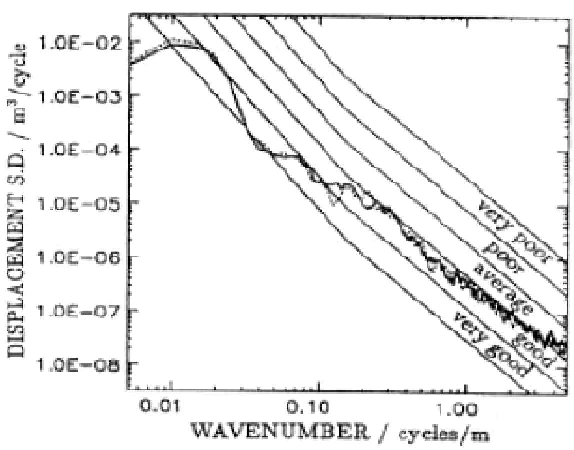

Fig. 1. Draft ISO classification for road roughness spectral densities

ii) Robson [9] also suggested that an adequate description of road profile spectra can often be given by an equation of the form:

$$S_u(\kappa)=S_0\left|\kappa\right|^{-n} \quad (2)$$

where n = 2.5 and S_0 is given as follows:

$S_0/10^{-8}$ $m^{0.5}cycle^{1.5}$ = 3-50 for motorway, 3-800 for principal road and 50-3000 for minor road [9].

iii) Gobi and Mastinu [10] considered two different power spectral densities for modeling the road irregularity, one of the $1/\omega^2$ form and the other of the $1/(\omega^2 + s_c^2)$ form (where $s_c = \alpha v$, α = constant and v = vehicle speed). They found that for $1/\omega^2$ form of road irregularity, the optimal suspension parameters do not depend on vehicle speed, whereas for a complex road spectrum irregularity (of the form $1/(\omega^2 + s_c^2)$), the optimal suspension parameters depend on the vehicle speed.

iv) Measurements of road profiles [11] have indicated that the surface irregularities may be treated as stationary Gaussian random process with zero mean and characterized by a single sided power spectral density of the form:

$$\phi(\omega)=(2\alpha v\sigma^2/\pi)/(\alpha^2v^2+\omega^2) \quad (3)$$

where, σ^2 = Variance of road irregularities (m^2);
α = Coefficient depending on the shape of road irregularities (m^{-1});
v = Vehicle forward speed (m/s);
ω = Temporal frequency (rad/s).

The road excitation model for the vehicle from roughness representation (equation 3) can be written in time domain by using the shape filter of the form [11]

$$\dot{w}=-\alpha v w+\xi \quad (4)$$

where, $\dot{w}$ and w are road velocity and road displacement respectively,

ξ is a zero-mean white noise process with covariance function

$$E[\xi(t)\ \xi(t-\tau)] = 2\alpha v\sigma^2\delta(t) \quad (5)$$

where, δ(t) denotes the Dirac delta function.

2.3 Road Damage

Road damage refers to degradation of structural integrity or surface profile of a road when it is trafficked by vehicles [6].

2.3.1 Types of road damage

Kennedy *et al* [12] list the following most important road damage mechanisms:

i) Fatigue cracking for all types of pavements;
ii) Permanent deformation (longitudinal rutting) for flexible and composite pavements;
iii) Reduced skid resistance for flexible and composite;
iv) Low temperature cracking for flexible pavements;
v) Reflection cracking for composite pavements;
vi) Faulting, spalling, low temperature and shrinkage cracking, blow-ups, punch-outs and steel rupture for rigid pavements.

Vehicles directly affect fatigue cracking and permanent deformation. Since composite pavements are rarely used as a new construction [7], only the following three types of damage mechanisms are considered in this paper:

i) Fatigue cracking of flexible pavements (Refer fig 2);
ii) Rutting of flexible pavements (Refer fig 3);
iii) Fatigue cracking of rigid pavements (Refer fig 4).

2.3.2 Road damage mechanisms

Most of the pavement design literature [7, 13-15] considers the issue of road damage caused by vehicles, mostly based on the notion that vehicles apply constant (static) tire forces on the road surface. Tire pressure is taken to be the design pressure in these cases. The laws governing fatigue damage and rutting of pavements are discussed as follows:


Fig. 2. Fatigue cracking in flexible pavements [6]

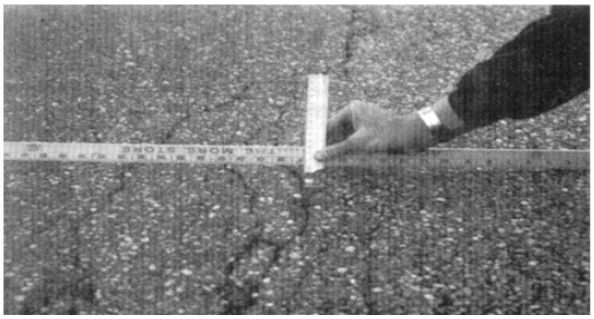
Fig. 3. Rutting in flexible pavements [6]

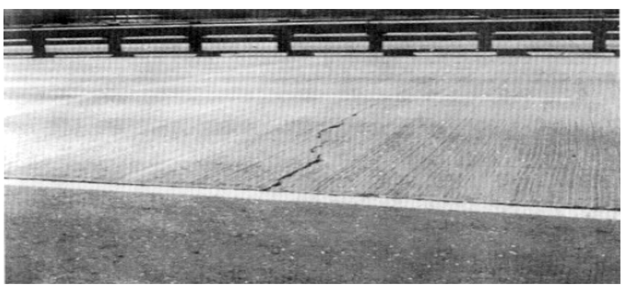
Fig. 4. Fatigue cracking in rigid pavements [6]

2.3.2.1 Fatigue damage

For the analysis of fatigue damage, the horizontal tensile stress or strain at the bottom of the asphalt or PCC surface layer at a point lying along the axis of the load is used in the design calculations (Fig. 5). Pavement designers assume that the crack propagates vertically upwards towards the surface from this layer interface. The development of fatigue laws have been carried out through two main approaches:

i) Phenomenological approach and
ii) Fracture Mechanics based approach

Phenomenological approach uses power law relationships of the form:

$$N_f = k_1 \varepsilon_t^{-k_2} \tag{6}$$

where,
N_f = number of cycles for failure,
ε_t = tensile strain (or stress) at the bottom of asphalt layer,
k_1= constant that depends on the stiffness of Asphalt,
k_2 = constant depending on the material and mode of distress (varies between 1-8 and is often taken to be 4).

Fracture Mechanics based approach is based on Paris law given by:

$$da/dN = A(K)^n \tag{7}$$

where, da/dN – crack growth rate,
K – SIF or its change and
A and n are the empirically determined constants.

References [16, 18-20] use the Fracture Mechanics based approach whereas [17] uses both the approaches, to study pavement damage. Ramsamooj [16] derived an expression for SIF (Stress Intensity Factor) for a crack in a pavement subjected to moving vehicular loads. The results were used to predict the fracture and fatigue of three kinds of pavements: Flexible pavements, rigid highway pavements and rigid airport pavements. It was shown that the fatigue cracking is likely to lead to failure by fracture with rapid or unstable crack propagation in a typical flexible highway pavement and a typical rigid airport pavement, but not in a typical rigid highway pavement. Collop and Cebon [17] considered both the approaches to pavement fatigue and concluded that the majority of pavements will tend to fatigue from the base of the asphalt layer. The surface cracks act as starter cracks and grow only under the presence of thermal loading cycles, whereas base cracks are not influenced by thermal loading cycles and grow due to applied vehicular loads. Ramsamooj, *et al* [18] used the weight function method to determine the SIF's for cracks and joints in highway and airport pavements. They developed certain relations for obtaining deflections and bending stresses in the slab at any particular location. These equations are useful in the design of rigid pavements.

Both the approaches, i.e. Phenomenological approach and Fracture Mechanics based approach use regression constants that cannot truly reflect the material properties. Hence, Liang and Zhou [19] developed a Fracture Mechanics based fatigue law which utilizes fundamental material parameters including fracture toughness, flexural tensile strength as well as other two quantifiable model parameters, i.e. damage parameter α and critical plastic zone length δ_c. The developed fatigue model predicts a much faster crack growth rate compared to the Paris Law and appears to be more sensitive to the ratio of the initial SIF over its critical value. Castell et al [20] identified two different crack growth rates in pavements. The first is associated with the tensile stress at the bottom of the surface course. The second one is caused by the tensile stress at the top of the surface course when the load is ahead or behind the crack. It is concluded that the growth rate for surface cracks (growing downwards) is much smaller than the internal crack growth rate (growing upwards).

2.3.2.2 Rutting:

Rutting damage in flexible pavements is the result of permanent deformation in each of the pavement layers. The number of cycles to failure (N_f) in case of rutting and the compressive strain at the top of subgrade ε_c (Fig. 5), are related by:

$$N_f = k_3 \varepsilon_c^{-k_4} \tag{8}$$

where k_3 and k_4 are constants.

If the road is assumed to be linear viscoelastic, then the average increase in rut depth is proportional to F/V, where F is the static load and V is the vehicle speed [21, 22]. This relation is approximately comparable to Eqn.(8) with k_4 =1.

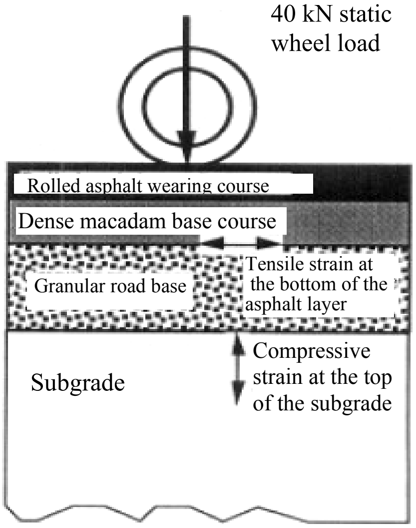

Fig. 5 Strain components used in mechanistic design of a typical flexible pavement from [6]

2.3.3 Road response

The response of road to vehicle-induced loads is required in order to predict the damage as per eqn (6) and eqn (8). The loads induced by vehicles on road are, in general, random in nature. The response (stress, strain and displacement) of the pavement to such loads is simulated by Cebon [23] and also separately by Hardy and Cebon [24] using convolution integral method. Both time domain and frequency domain solutions are presented. In both the papers, the theory is validated using data from full-scale tests. Hardy and Cebon [24] tested the assumptions of linearity and isotropy that are required by the theory and found that they are sufficiently satisfied. The response of the test road was found to be very sensitive to temperature. The measured and predicted strains in the test road and in the simple road model were found to decrease significantly as the speed increased. Collop *et al* [25] and Gillespie *et al* [21] considered flexible pavement to be viscoelastic and derived the expressions for rutting damage of flexible pavements. According to this (linear viscoelastic) theory, the average increase in rut depth is proportional to F/V, where F is the static load and V is the vehicle speed.

2.3.4 Road damage criteria

Most of the civil engineering literature uses static vehicle load for design of pavements. They have achieved mixed success due to very complex nature of road damage problem. But the role of vehicle dynamic loads in pavement design is still not completely known. Some of the major performance criteria considering road damage are listed as follows [6]:

2.3.4.1 Fourth Power law [26]

During 1958-60, American Association of State Highway Officials (AASHO) conducted extensive road tests taking a large sample of road vehicles and road tracks. They finally came up with a criterion, the fourth power law, which laid the foundation for efficient pavement design. The loads applied to a road by a mixed traffic can be converted into a number of Equivalent Standard Axle Loads (ESALs) by applying the fourth power law to each axle. The number of ESALs (N) attributed to static load P kN per axle is:

$$N = (P/P_0)^n \tag{9}$$

where,

P_0 is the standard axle load (80 kN) and n is the damage exponent equal to 4. Thus, this law states that the damage in pavement caused by per pass of P kN single axle load is equivalent to $(P/80)^4$ times the damage caused by per pass of an 80 kN single axle load.

2.3.4.2 Eisenmann's Road stress factor [27]

The expected value of the fourth power of the instantaneous wheel force is known as the 'road stress factor' and is given by:

$$\phi = E[P(t)^4] = (1 + 6\overline{s}^2 + 3\overline{s}^4)P_{stat}^4 \tag{10}$$

where,
P(t) is the instantaneous tire force at time t,
$P_{stat} = E[P(t)]$ = static (average) tire force,
E[ ] = expectation operator,
$\overline{s}$ = Dynamic Load Coefficient (DLC)

$$= \frac{\text{RMS dynamic tire force}}{\text{Static tire force}} \tag{11}$$

2.3.4.3 Aggregate tire forces [28]

The aggregate tire force at a particular point along the wheel path is simply the summation of the dynamic tire forces applied at that point by all the axles of a vehicle and is given by:

$$A_k^n = \sum_{j=1}^{N_a} P_{jk}^n \qquad k = 1, 2, 3\ldots\text{Ns} \tag{12}$$

where
A_k = aggregate tire force at point k along the road,
P_{jk} = the force applied by tire j at location k,
Na = number of axles on vehicle,
Ns = number of points being considered along the wheel path and n = damage exponent,
Note: n =1 is suitable for rutting [6, 21],
n = 4 is suitable for fatigue damage in which case $A_k^n = A_k^4$ is called aggregate fourth power force [6].

2.3.4.4 95th percentile forces [29]

95th percentile level of the aggregate 4th power force (R_{95}) is a suitable criterion for assessing fatigue damage potential of the vehicle. If roads are considered to be spatially repeatable in nature then we say that the road is damaged when the worst 5% locations on the road undergo failure.

2.3.4.5 Single vehicle pass road response calculations [21, 28, 29, 30]

'Single vehicle pass' calculations determine the incremental road damage due to one passage of a vehicle over a particular road. The procedure involves simulating the vehicle response to road profile induced vibrations. Through the simulations we get the vehicle-induced loads as a function of the distance along the road surface. These loads are then combined with the road response influence functions to get the road response (stresses, strains and displacements) as a function of time, at each point along the road. Through this strain-time history, numbers of load cycles are calculated using a suitable method (peak counting method or rainflow method [21]). Then the theoretical road damage at each point along the road due to the passage of a single vehicle is determined using:

$$D_k = \sum_{j=1}^{N_\varepsilon} \frac{1}{N_{jk}} \qquad k = 1, 2, 3\ldots\ldots N_s \qquad (13)$$

where,

N_{jk} – the number of cycles to failure at location k due to strain cycle j, calculated using eqn (6) and eqn (8);

N_ε – the number of strain cycles incurred at each point on the road;

N_s – the number of calculation points along the road.

2.4 Assessment of road damaging potential

There is considerable interest throughout the world in introducing regulations, which encourage the use of heavy vehicles that cause less road damage. For doing this, it is necessary to have an assessment criterion, which can rank the vehicles according to their road damaging potentials. Several researchers [31-35] have proposed methods for assessing 'road-friendliness' of heavy vehicles. This is an important topic, for the highway agencies, which are involved in setting and enforcing vehicle regulations, and the vehicle industry, which has to satisfy these requirements.

Cole and Cebon [32] proposed three quantities by which the road damaging potential of the HGV can be measured. These are:

a) *The 'primary response' of a test pavement (stresses, strains and displacements):* However, in this case the road damaging potential will be affected by the environmental factors and the constructional details of the pavement.

b) *Dynamic tire forces:*

This can be done in three ways:

i) Vehicle mounted instrumentation – impractical for large number of vehicles.

ii) 'Road Simulator' (hydraulic test stand) – Good for large number of vehicles but expensive.

iii) 'Tire force measuring mat' – Good for large number of vehicles and less expensive [36].

c) *Measurement of vehicle suspension parameters:*

Even though there is no established relationship between suspension parameters and road damage, this approach is proposed by the Commission of EC for defining 'equivalent air suspension' [31]. This method involves deducing a single resonant frequency and damping ratio from the measured suspension deflection of a tractor drive axle, during a transient event. To be equivalent to an air suspension, a leaf spring suspension must have a resonant frequency less than 2 Hz and a damping ratio greater than 0.2, with at least half of the damping being generated by hydraulic shock absorbers. (Air suspensions were considered to be more road-friendly than steel suspensions). It was found that the parametric test such as EC proposal [31], which makes the use of a single frequency and a single damping ratio, cannot be used to assess the road damaging potential of HGVs. Also it is necessary to carryout the test on the whole vehicle instead of a single axle to get correct assessment of the road damaging potential.

Potter *et al* [33, 34] separately proposed two methods for assessing the road damaging potential of heavy vehicles. These are (i) convolution method (linear method) and (ii) The parameter estimation method (non-linear method). They found that use of Convolution method showed unexpectedly large errors and only the parameter estimation method was suitable for assessing road damaging potential of heavy vehicles. Potter et al [35] reviewed various testing methodologies used to assess road damaging potential of HGVs. They confirmed the previous conclusions proposed by Cole and Cebon [31]. In addition they found that, ranking of the axle group suspensions depends on the pavement damage criterion used. Aggregate fourth-power damage criterion is more suitable than DLC or stress factor (Φ) if the loads are spatially repeatable, which agrees with the findings of Potter et al [29].

3 Vehicle-Road Interaction

The forces between the vehicle and the road surface are of two types:

i) The static vehicle load, which includes the weight of the vehicle and payload; and

ii) The dynamic load, which is caused due to vibration of vehicle body on uneven road surface.

The sum of the static and dynamic loads is called the instantaneous tire force and is denoted by P(t). Due to this load, stresses are induced in the pavement, which may ultimately lead to its failure as per eqn (6) and eqn (8).

3.1Vehicle Simulation

Many papers on vehicle simulation are available in literature (see for example review paper [37]) but only a few of them are discussed here. Virchis and Robson [22] computed the response of an accelerating/decelerating vehicle to randomly undulating road surface. It was shown that for practically occurring values of forward acceleration, mean square response differs very little from that with zero acceleration (constant velocity) and hence the random road surface can be assumed to be a stationary ergodic process.

Gadala *et al* [38] modeled a tractor semi-trailer traveling over a random surface using finite element and analytical methods. The vehicle linear models were constructed in such a way as to describe the bounce and pitch modes of the tractor and the semi-trailer, bounce of each wheel-axle assembly and also to account for the semi-trailer beaming effect. Cole and Cebon [39] validated their vehicle simulation, using tests performed on typical UK articulated vehicles, for the following 3 types of vehicle models:

(i)A 6 dof, 2D trailer suspension model.

(ii) An 11 dof, 2D tractor and trailer model.

(iii) A 21 dof, 3D whole vehicle model.

Based on the tests and computer simulations, they concluded that the sprung mass roll motions do not contribute significantly to tire forces. But if sprung mass roll modes are to be considered then it may be necessary to use 3D model.

Recently Turkay and Akcay [40] studied the response of a vehicle to profile imposed excitation for a 2 dof quarter car model. The response of the vehicle to both white and colored noise velocity road inputs was studied. For colored noise, subspace-based identification algorithm was used to design linear shape filter. Best results were obtained for a higher-order shape filter. The integrated white noise approximation to the road displacement spectrum yielded more accurate results than those of the second order linear shape filter with colored noise input. But at high speeds, in particular for v $\geq$ 100km/hr, this approximation was seen to be unacceptable.

From all these studies it can be said that the methods for simulating vehicle response for random road excitations are well developed. In most of the cases a 2-dimensional vehicle model can suffice. However, based on the vibration modes of sprung and unsprung masses, a 3-dimensional vehicle model or a continuous system vibration analysis may be required. Also the effect of acceleration/ deceleration being very small on ride comfort, the road profile could be assumed to be stationary and ergodic process. However, the effect of acceleration/ deceleration on road damage has to be investigated, since the latter is proportional to the fourth power of the dynamic wheel load.

3.2 Vehicle induced road damage

There have been two main approaches to estimate the road damaging effects of dynamic tire forces. Some researchers believe that the loading at each point along the road is essentially random such that damage is uniformly distributed along the road. Other researchers believe that the peak forces applied by the heavy-vehicle fleet are concentrated at specific locations along the road. This effect has been termed as *spatial repeatability*. Under these circumstances some locations along the road may be expected to incur more damage than others. The 95th percentile road damage criterion was used by Cebon [28] with a six dof tandem axle vehicle model. The author found that, the road damage caused by dynamic tire forces generally increase with speed. There exist certain speeds at which pitch coupling between axles results in significant increase in the damage incurred at particular points along the road. The 95th percentile road damage may be around 4 times the static damage. On roads with relatively smooth surface profiles at high speeds, the increase in dynamic wheel loads with speed may be outweighed by the decrease in road surface dynamic response. The net effect may be a reduction in fatigue damage for speeds greater than 100 kmph.

Potter *et al* [29] conducted a series of tests on British Trunk road in which the dynamic tire forces generated by approximately 1500 HGVs were measured using a load measuring mat. The data were used to investigate the relative road damaging potential of various classes of vehicles. Two criteria were used to rank axle groups in terms of road damage (i) Average dynamic load coefficient (DLC) which assumes random nature of dynamic tire forces, and (ii) 95th percentile aggregate 4th power force which assumes spatially repeatable nature of dynamic tire forces. The authors considered only fatigue damage for their study. They concluded that the ranking of axle group suspensions depends on the pavement damage criterion used, i.e. DLC or aggregate 4th power criteria. The aggregate 4th power criterion is considered to be more realistic approach. Also they found that, on average, air suspended vehicles generate smaller dynamic loads and hence caused less road damage than steel suspended vehicles. However, some air suspended vehicles with inadequate suspension damping were found to generate very high dynamic loads and consequently, very high levels of road damage.

One of the methods for assessing the spatial repeatability of dynamic tire forces is Spatial Repeatability Index (SRI) [41] given by:

$$SRI = \frac{\sigma_{uv} - \mu_u \mu_v}{\sqrt{(\sigma_u^2 - \mu_u^2)(\sigma_v^2 - \mu_v^2)}} \tag{14}$$

σ_{uv} - Covariance between u and v,

σ_u^2 , σ_v^2 - variances of u and v,

μ_u , μ_v - mean values of u and v.

i.e. SRI is nothing but correlation coefficient between an aggregate tire force history u and a reference aggregate force history v. Two aggregate force histories can be considered to be repeatable if SRI $\geq$ 0.707, corresponding to a phase difference of 45^o (cos45 = 0.707) [41]. Based on the study of 36 vehicle models and a reference model, Cole and Cebon [41] estimated that approximately two-thirds (67%) of the leaf-sprung heavy articulated vehicles may contribute to a repeated pattern of road loading.

Cole *et al* [42] carried out two test phases of experiments to check the loading patterns of typical heavy vehicle fleet. In phase I experiments, the measured dynamic tire forces generated by 14 articulated vehicle combinations (3 tractors + 5 Trailers) are used to confirm previous theoretical predictions [41] of spatial repeatability. In Phase II tests the dynamic tire forces generated by over 1500 HGVs traveling on a British Trunk Road were used to estimate the degree of repeatability exhibited by a typical highway fleet. Approximately half of the vehicles tested on the A34 (Phase II) in the normal flow of traffic were found to contribute to a spatially repeatable pattern of pavement loading (in contrast to 2/3rd as obtained in [41]). The implication of the studies [41, 42] is that road failure is likely to be determined by peak forces rather than average or rms dynamic forces.

3.3 Interaction between tractor and trailer

The dynamic interaction between the tractor and the trailer units plays an important role in road damage. Consequently, we need to seek answer for the following two important questions:

i) Does every tractor/ trailer combination have to be tested as a coupled unit or is it possible to rank suspension performance (in terms of road damage) by testing all tractors using a standard trailer or all trailers using a standard tractor?
ii) Can the road damaging qualities of the suspension be assessed by measuring the loads generated by individ-

ual axle groups or is it necessary to examine the road damage done by the whole vehicle?

Potter *et al* [30] used 14 vehicle combinations (3 tractors + 5 trailers) to investigate the dynamic interaction between the tractor and the trailer units. For rutting a power of n=1 is used in the aggregate force criteria and for fatigue a power of n=4 is used. They found that:
(i) Rutting damage is governed by the gross vehicle weight whereas individual axle loads govern fatigue damage. Consequently, dynamic loads are not very important in case of rutting damage but they play a major role in fatigue damage [21]. (ii) Ranking of vehicles in terms of the road damage does not depend on strength of the road [21]. (iii) It is possible to measure the dynamic loading performance of tractor suspensions using a standard trailer. However, trailer suspensions cannot be assessed using a standard tractor. (iv)The influence of trailer suspensions on road damage done by the whole vehicle can be estimated by measuring the dynamic loads generated by the trailer alone. Conversely, it is only possible to assess the effect of the tractor suspensions on damage done by the whole vehicle by measuring the dynamic forces generated by all axles.

Cole and Cebon [43] introduced Dynamic aggregate force coefficient (DAFC) to study the dynamic interaction between tractor and trailer units:

$$\text{DAFC} = \frac{\text{Standard deviation of a(t)}}{\text{Mean value of a(t)}} \tag{15}$$

where $a(t) = \sum_{k=1}^{N} f_k(t + T_{1k})$, T_{1k} is the time delay between the first (steering) axle and axle k. However, they found that Correlation coefficient when assessing trailers was higher than when assessing tractors i.e. trailers can be assessed using a standard tractor. This result contradicts with the findings of Potter *et al* [30].

Cole and Cebon [44] have shown that the following three conditions govern the dynamic interaction between the tractor and trailer units of heavy articulated vehicles: (i) Large variation of modal force excitation with frequency. (ii) Large variation of phase angle between modal forces with frequency. (iii) Pitch and bounce mode responses that are of similar amplitude, combined with natural frequencies that are in sufficient proximity to allow constructive and destructive addition. The effect of truck weight and dimension regulations is that the three conditions are likely to exist in a large proportion of articulated trucks. Front-rear interaction should therefore be considered when assessing the road-damaging potential of tractors and trailers.

3.4 Whole Life Pavement Performance Model (WLPPM)

Single vehicle pass road response calculations are described already in section 2.3.4.5 and are used in references [9, 28, 29, and 30]. In a WLPPM, a vehicle simulation is used to generate dynamic tire forces that are a function of the distance along the road. These dynamic tire forces are then combined with the appropriate pavement primary response influence functions (stresses, strains and displacements) to give primary response histories at regularly spaced points along the pavement. These are then transformed into pavement damage (fatigue and rutting) using an appropriate damage model. The result is an increment of damage at each point along the pavement due to a single vehicle pass. The pavement surface profile is then updated to reflect permanent deformation damage and the layer material parameters are changed to reflect fatigue damage (change in modulus of elasticity and stiffness). The procedure is then repeated for the next vehicle pass (until the road is entirely damaged).

The WLPPM was used by references [45-48] to study the long-term performance of flexible pavements. Collop and Cebon [45, 46] used the WLPPM to investigate the relationship between ‘hot spots’ (due to peak dynamic loads), ‘weak spots’ (due to initial pavement stiffness variation) and long-term pavement wear. Overall it was concluded that both the dynamic tire forces and the asphalt layer thickness variations can significantly influence the long-term flexible pavement performance. Collop *et al* [47] used the WLPPM to evaluate the relative importance of spatial repeatability on long term pavement damage for three typical British road constructions: motorway, principal road and minor road. A new parameter called Spatial Distribution Number (SDN) defined as the standard deviation of the SRI probability distribution was identified as a suitable parameter for characterizing the degree of repeatability exhibited by a vehicle fleet. A typical heavy vehicle fleet was found to have an SDN of 0.287. (Note that SDN=0 corresponds to high repeatability and SDN= ∞ corresponds to no repeatability). Based on this study it was found that thinner pavements are most sensitive to the level of spatial repeatability exhibited by the vehicle fleet. Collop and Cebon [48] used WLPPM to investigate the long-term flexible pavement performance for ‘road-friendly’ air suspensions and steel suspensions. It was concluded that changing to a fleet of ‘road-friendly’ air-suspended vehicles would not significantly affect the life or the maintenance cost of thicker asphalt pavements (motorways and trunk roads) where the mode of failure is permanent deformation/ rutting. However the life of the thinner pavements (minor roads), which fail by, fatigue damage and pot-holing would be increased significantly if the vehicle fleet changed to ‘road-friendly’ air-suspensions. Cebon [49, 50] has reviewed the literature concerned with road damage caused by the heavy commercial vehicles.

4 Suspension Modifications

Based on the discussion so far it can be seen that dynamic loads of heavy vehicles have a significant contribution in causing damage to the pavements. These dynamic loads depend on suspension parameters, such as suspension spring stiffness and damping ratio. However, the relationship between suspension parameters and road damage is not well understood till date. As mentioned earlier any vehicle suspension should have high level of ride comfort; good road holding capacity (i.e. high roll-over stability); minimum suspension working space/ rattle space and should cause minimum amount of road damage. The above said requirements are conflicting with each other and therefore we need to optimize the suspension to satisfy all these requirements simultaneously. Since a typical passive system cannot cater to all these requirements simultaneously, more advanced suspensions such as semi-active and active suspensions have been proposed in the literature.

4.1 Optimal passive suspensions

Some researches [51-53] studied the passive suspension optimization from the road damage point of view. Cole and Cebon [51] used a 2-dimensional, 11 dof mathematical model of a tractor (with two axles) and a semi trailer (with tandem axle arrangement) to study the effect on dynamic tire forces of the following three modifications to the trailer suspension: (i) Softer springs (half the stiffness), (ii) Elimination of the spring-end friction (using rubber blocks), and (iii) Hydraulic dampers. The simulations indicated approximately 31% decrease in trailer-axle DLCs and 13% decrease in the road damage by trailer axle. Using these changes on a test vehicle they found that the measured reductions in the dynamic tire forces were approximately half of those predicted by simulation. Using a 2 dof bounce model, Cole and Cebon [52] found that to minimize road damage a suspension should have 1/5th the stiffness and twice the damping of a typical air suspension for typical input conditions. For a given roll-over threshold and optimum damping and for the typical parameters chosen, the use of anti-roll bar with soft springs alone and independent suspension causes less road damage than a rigid axle suspension. Also, they found that optimizing the suspension stiffness and damping results in a 5.8% reduction in road damage by the whole vehicle (averaged over 3 speeds). Lu Sun [53] considered the probability of peak value of tire load exceeding a value α as an objective function for optimization where:

$$P\text{ (peak value of tire load exceeding } \alpha) = \exp\left(-\frac{\alpha^2}{2\sigma_f^2}\right) \qquad (16)$$

where σ_f = standard deviation of tire loads. It was shown that the tire with high pressure (i.e. more stiffness) results in more damage in pavement structures. Also it was shown that, large suspension damping and large tire damping are of benefit to the reduction of tire loads (and hence road damage). Recent developments in the design of optimal passive suspension involve use of Genetic Algorithms [54-56]. Genetic algorithm is used in [54] to minimize the RMS seat acceleration for a 1DOF system. Also, a multidisciplinary approach has been used to design a combined active-passive suspension system wherein optimization has been done using Genetic Algorithm [55]. In [56] dynamic tire load is minimized by genetic algorithm of quarter truck model to get optimum value of suspension parameters as well as tire stiffness.

4.2 Semi-active suspensions

As passive suspensions are simple, reliable, and inexpensive, they remain dominant in the automotive marketplace even till date. However, due to their potential benefits, active and semi-active suspensions for ground vehicles have been a very active subject of research [37]. They have recently been commercialized on high performance automobiles. Development of active suspensions started in the 1950's. Many analytical and experimental studies on active and semi-active suspensions to improve ride quality and handling performance have been performed. The conclusion is that active and semi-active suspensions can provide substantial performance improvements over passive suspensions in general and semi-active suspensions can be nearly as effective as fully active suspensions.

Hedrick *et al* [57] investigated semi-active control laws to reduce dynamic tire forces. It has been shown in their study that tire-force feedback system is better than sprung mass velocity feedback and passive system. The study shows that the comparison of frequency responses of quarter car model indicates that the performance of semi-active suspension is close to the best passive suspension for all frequency ranges in minimizing the dynamic tire force. For experimentation purpose they used half car model subjected to sum of six sine waves road input and the results obtained showed reduction in peak dynamic tire force by 40%.

Cebon *et al* [58] used three strategies for controlling the semi-active damper:

i) Modified Skyhook Damping (MSD)
ii) On-off control and
iii) Full state feedback control (FSF)

The experimental set-up consisted of the Hardware-in-the-Loop (HiL) test rig. The main aim of their study was to establish the possible improvement in performance (i.e. minimizing body acceleration and road damage) using the above three control strategies. It was found that:

(i) For the conditions investigated in this study, using semi-active modified skyhook damping (SAMSD) control, rms tire force and rms body acceleration could be reduced simultaneously by at least 13% and 22% of the responses for optimal passive damping.
(ii) On-off damping control was found to achieve reductions in rms tire force comparable to continuous SAMSD damper control with less working space usage; however the body acceleration levels produced were larger.
(iii) Using semi-active full stage feedback (SAFSF) control it was found that the body acceleration and the rms tire force could be reduced simultaneously by 28% and 21% of the values for optimal passive damping.
(iv) If either the dynamic tire force or the body acceleration is to be minimized individually, SAFSF gives better performance than the SAMSD control. However, if the tire force and the body acceleration are to be minimized simultaneously, SAMSD is a good substitute for SAFSF control.
(v) Semi-active dampers are more effective in reducing dynamic tire forces (and the resulting road damage) on rough roads than on smooth ones.

The results of project DIVINE (1997) by Valasek *et al* [59] proved that the dynamic part of road-tire force of heavy vehicles causes significantly increased damage to roads and increased loading of bridges. One way to reduce dynamic tire forces is to use advanced suspension systems such as active or semi-active suspensions. Valasek *et al* [60] studied several strategies for controlling the semi-active damper.

The selection of the suitable control strategy is based on minimization of the dynamic load stress factor (DLSF) (Refer eqn.10):

$$DLSF = 1 + 6(DLC)^2 + 3(DLC)^4 \qquad (17)$$

where, DLC is the Dynamic Load Coefficient (eqn.11).It was found that non-linear extended ground hook (EGH) and the fuzzy control concepts gave better results. The semi-active truck suspensions were found to reduce the truck tire forces by about 10-30% without adverse effects on ride comfort. This corresponds to a reduction of road damage up to 70% or to a possible payload increase by 1 ton for 10 tonnes of original payload.

Kitching *et al* [61] introduced two new linear state feedback control strategies: aggregate force feedback control and road damage feedback control, which are closely related to road damage. Comparison was made with two existing control strategies, viz, LQR and preview based control. The relative performance of the four controllers was examined using a 2-axle 4-dof planar vehicle model, with both active and semi-active suspensions. Overall it was found that the preview-based controller was the most consistently effective suspension for reducing the road damage with a semi-active suspension. The 4 dof model simulations with motorway input conditions predicted that the LQR controlled semi-active suspension could reduce both the road damage and the rms body acceleration simultaneously by 8.9 and 20.2% respectively compared with an optimum linear passive suspension. Using a preview controller further improved the performance of the semi-active suspension, such that the corresponding improvements in road damage and rms body acceleration were 17.8 and 33.8%. These improvements were achieved without any increase in the rms working space.

4.3 Active suspensions

Much of the literature [e.g. 62-67] concerned with active suspension design is for passenger vehicles and hence road damage as a design criterion is not directly considered in these studies. Hrovat [64] investigated the influence of unsprung mass on ride and handling quality of active suspension vehicles modeled as quarter car 2-dof systems. The results demonstrated that for active suspensions, both ride and handling can be improved by reducing the unsprung mass. In the limit, when unsprung mass equals zero, the 2-dof configuration reduces to a 1-dof. For most road/speed conditions, the limiting, 1-DOF model results in the best performance with respect to given ride /handling characteristics. Thus, the 1-dof model serves as a reference as indicating maximum ride improvements that are possible with any 2-dof model. Hrovat [65] suggested the use of passive dynamic absorber on the unsprung mass to achieve better ride and handling characteristics from a 2 dof quarter car model. This study revealed that by the use of active dynamic vibration absorber, the rms sprung-mass acceleration could be reduced ten times as compared to passive suspension system under same or even smaller suspension and tire deflection.

By using the discrete time, optimal Linear Quadratic (LQ) control formulation, and a 2D, 4-dof half car model, Hrovat [66] has shown that the preview based on front wheel input contributes to up to 70% reduction of vehicle rms acceleration, for a given suspension travel and up to 50% reduction in tire deflection, for a given acceleration level. These improvements are in addition to those already achieved through active suspensions without preview. Also, this preview control is most beneficial at higher speeds and rough roads. If a suitable sensor were available then the performance could be further improved with road preview ahead of the front wheel. A good survey of the applications of optimal control techniques to the design of active suspensions, for simple quarter car 1D models (1-dof and 2-dof models), and their half car 2D and full car 3D counterparts can be found in Hrovat [67].

ElMadany published a series of research papers [68-73] on active suspension design and analysis for suspension performance improvement. Most of studies made by him are for heavy vehicles i.e. for articulated multi-axle vehicles like tractor semi-trailer for which passive suspension gives poor ride comfort and rough vehicle handling especially at higher speeds. The main thrust of his studies was to improve cabin performance of tractor semi-trailer. Holdman and Holle [74] modeled a heavy-duty truck in SIMPACK to see the effect of active, semi-active and adaptive dampers. Three different suspension systems studied by them are as follows:

i) Active Sky-hook damper,
ii) Semi-active Sky-hook damper,
iii) Adaptive damper: standard, soft, and hard.

Following conclusions have been revealed from this study:
(i) For a passive system up to 4Hz, a hard damper assures driving comfort as well as driving safety. For frequencies from 4 to 8 Hz, the damper should be as soft as possible to achieve good results for both criteria. For higher frequencies, a soft damper minimizes the body movement and hard damper minimizes the dynamic wheel loads. In case of adaptive systems the standard value should be used.
(ii) The dynamic wheel loads of the semi-active and the active skyhook systems show better result than standard system in the region of the body natural frequency. The results are 12 to 25% lower than the results of the standard system.

5 Major Conclusions

Following are important conclusions from literature:
(i) The response of the road surface can be considered to be linear, isotropic depending on the frequency of the applied loads and highly sensitive to environment.
(ii) The mechanisms by which roads suffer damage due to vehicle loads are not fully understood.
(iii) Dual tires generate lower ground contact pressures and therefore less road damage than wide base single tires for the same static load.
(iv)Variations in tire contact conditions including the number and type of tires on an axle, contact area and pressure distribution mainly influence fatigue and rutting damage just below the surface of flexible pavements, particularly for thin wearing courses. Subgrade rutting and fatigue damage in thicker pavements is largely governed by the total dynamic wheel load.
(v) Individual static axle loads are much more important than gross vehicle weight in fatigue damage, whereas the opposite is true for rutting. The ranking of vehicles for each type of road damage appears to be largely independent of the strength of the road.

(vi) Dynamic tire forces, in general, increase with vehicle speed and road roughness and are spatially repeatable.
(vii) Theoretical road damage increases with vehicle speed and road roughness, but it may decrease at higher speeds due to decreasing dynamic response of the road structure.
(viii) Most vehicles generate their dynamic tire forces because of sprung mass motion in the 1.5-4 Hz frequency range, but some poorly damped axle group suspensions (such as walking beam suspensions) also generate a large component at 8-15 Hz, due to unsprung mass vibration.
(ix) The stiffness and damping properties of each suspension affects the dynamic tire forces generated by each other suspension. Hence, the road damaging potential of an HGV cannot be assessed using a parameter measurement prescribed by EC [31].
(x) The effects of structural vibrations, roll-plane motion and tire non-uniformities are small and can be neglected.
(xi) Multiple axle suspension systems generally rank in the following order of increasing road damage:

Air spring, < Four spring, < Walking beam,
Torsion bar Six spring Single point

(xii) Depending on the method of analysis and the assumptions, dynamic wheel loads increase road damage by a factor 1.2-4 for typical vehicles and operating conditions.
(xiii) Viscous damping and soft spring are desirable for minimizing dynamic loads. Dry Coulomb friction is undesirable.
(xiv) Suspensions with optimal passive damping and soft springs can be improved significantly by the use of semi-active suspensions.
(xv) Minimization of probability of peak value of tire load exceeding certain limiting tire load value is considered to be the best way to reduce road damage.
(xvi) More recently, Genetic Algorithms are being used for optimizing road friendly suspension systems.

In summary, the issue of vehicle-road interaction has been studied in past and several criteria for vehicle induced road damage have been proposed. It is also shown that the dynamic tire loads are spatially repeatable and hence peak tire forces play a vital role in road damage instead of rms tire loads. The interaction between tractor and trailer units demands that the whole vehicle should be considered (instead of individual axles) while evaluating road damage.

6 Areas for research

From the literature survey, it is found that the issues listed below are either partially addressed or not addressed at all in the previous studies:
(1) Road damage being a very complex phenomenon, our understanding of road damage mechanisms is very limited at present. Also the relation between the suspension parameters and road damage is not well understood. For designing a vehicle suspension to reduce road damage the above two factors play a very vital role.
(2) The exponents k_2 [eqn. 6] and k_4 [eqn. 8] in the damage law are ambiguous. Generally, for fatigue damage, a value of $k_2 = 4$ is used, which is taken from the 4th power law and for rutting damage, a value of $k_4 = 1$ is used, which is based on viscoelastic approach to rutting damage. The higher value of k_2 or k_4 puts more importance to the individual axle loads and its lower value puts more importance to gross vehicle weight. Since a slight variation in the exponents can affect the road damage considerably, there has to be enough mathematical/ experimental proof to suggest that the above-mentioned values of k_2 and k_4 are reasonable.
(3) Most of the previous studies related to flexible pavements assume that the vehicle is traveling at the middle of the lane. The effect on road damage when a vehicle travels along the edge of the lane is a subject of future research.
(4) Both the road holding and the 'road-friendliness' criteria are related to the tire forces. But these two criteria are conflicting with each other. For example, good road holding capability requires higher tire forces which in turn cause more road damage. We need to understand the relationship between these two criteria in detail, so that we can decouple the two criteria and achieve improvements in both, instead of satisfying ourselves with a compromise. Cole and Cebon [46] have reported an improvement in road holding as well as a decrease in road damage by using anti-roll bar with soft springs and independent suspensions.
(5) Simulation of vehicle response to potholes and its effect on further road damage need to be investigated.
(6) For flexible asphalt road, effect of environmental conditions like temperature, rain etc. on road damage need to be explored.
(7) Studies related to multi-axle vehicle suspension design are limited up to improving driver cabin performance. Road damage due to multi-axle vehicles is more, hence there is urgent need to design road friendly suspensions for multi-axle vehicles.

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